Department of Mechanical and Aerospace Engineering

Potential Applications for Heat Recovery from the Longannet Cooling Water Outlet Flume

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Abstract

The main objective of this project was to understand the need for heat recovery at Longannet power station and to provide a feasibility study for the potential application of heat recovery technology. Heat recovery applications were discovered and reviewed based upon their both technical and economic standing and appropriateness for the project and for the cooling water outlet flume. Under much review and study, it was clear to see that heat recovery systems had been introduced to some sectors in the energy world, by the use of basic heat pump systems for hot water systems for homes and other buildings such as hotels and non-commercial applications. Furthermore it was clear that the vast amount of energy lost through the circulating water was quite significant, and there could a potential to use modern heat pump systems to further upscale some of the heat lost and provide this heating for either an onsite or offsite demand application. The literature review showed that for the basic temperature of the water at the outlet flume, heat pumps were the only heat recovery application suitable. After much review it was also clear that traditional heat pumps would not provide a high enough water outlet temperature with a good heat pump rating or COP level. It was ideal then to look into modern transcritical heat pumps using CO^2 as the working fluid that would provide a reasonable amount of heat for offsite applications. Further analysis in the project included a feasibility study into the potential of using these heat pumps for a district heating network to provide heat for space heating and domestic hot water, however a basic cost comparison analysis showed that the running of the heat pumps would not be competitive with the local prices using conventional heating fuels. It was clear from the technical analysis that these heat pumps could in fact be used well with other smaller scale applications or for a new building estate or community. It was evident that with older buildings, the level of heating standards and insulation would not be suitable for a modern and new district heating network. The project also outlines the possibility of using the upgraded heat for onsite applications such as a smaller heating network for drying biomass with underfloor heating systems and a basic investigation showed a good potential for smaller onsite use. The conclusions drawn from project outline a potential for some further work to look into an open/closed loop system combined with an onsite heat pump house with a circulating water loop.

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Nomenclature

°C	degrees Celsius
°F	degrees Fahrenheit
hr	hour
J	Joules
kg	Kilogram
kW	Kilowatt
kWh	Kilowatt hour
L	Litres
MJ	Mega joules
MW	Mega Watt
m	metres
m^3	metres cubed (volume)
min	minutes
MCw	Moisture Content wet
%	Percentage
s	seconds
t	tonne
vol	volume
yr	Year
Ft	Feet
G.P.M	Gallons Per Min
W	Work Done

Chapter 1: Introduction to the Project

1.1 Background and Motivation

Longannet power station is owned and operated by Scottish Power, which is part of the Spanish Iberdrola Group. Longannet power station has been operating since 1972 and is the largest generator of power in Scotland, with a total capacity of 2,400MW from four 600MW units, which can provide power to around 2 million households. It is clear that the station has played a major role in providing Scotland's energy from when it became fully operational in 1973. Longannet is also the second largest coal-fired plant in the United Kingdom and is located on an 89 hectare site on the north side of the shore of the Firth of Forth near Kincardine, Fife. The station is primarily a coal fired station, but the combustion process can also be supported by natural gas firing. Looking back at the station's output, levels increased from 9.139 GWh in 2011 to 9.525 GWh in 2012, however evidence from the station's reports shows that in some cases in the Spring and Summer months some of the units had been shut down due to network improvements reducing system capacity. The figure below shows the power station.

Now and in the future, the influence of increasing renewable generation will have an adverse effect on the operation and output from traditional generation methods such as coal fired power plants in the UK, and more particularly, Longannet power station. The increase of dynamic and unpredictable renewable generation is changing the way in which Longannet is being used to meet Scotland's supply and demand levels. It is clear that in the future when renewable capacity is increased, Longannet will be used as a means of back up rather than running at full capacity 24hours a day. Renewable capacity in Scotland has increased from 2.7GW in 2007 to 6.6GW in 2013, and capacity is set to increase by another 14GW in the future from a range of renewable technologies. Wind generation (onshore and offshore will continue to rise, and this will have an effect on conventional sources of energy and how they are used to meet Scotland's demand profile. At times of high winds, national grid has managed and reduced the output from the station, and in some cases has asked for some of the 600MW units to be switched off.

The station in the past few years has undergone serious redevelopments and improvements in order to maintain its high standards in a demanding and very unpredictable environment. It is clear that the station must enhance some of its operations to stick by one of its key principles, which is to commit to reducing its environmental impact. With the ever increasing financial incentives from the UK government to help increase non-conventional sources of energy, such as offshore wind, it is important that Longannet upgrades the power plant in order to secure a future in the power generation market. As the power station becomes older and closer to its end life, it is clear that Scottish Power are making best use of the existing technology onsite, while incorporating new technology to deal with some of the more pressing environmental issues associated with coal fire generation. The station over the past few years as carried out significant boiler improvements and a major project in replacing the original high-pressure turbine and transformer. Some other work included maintenance to boiler tubes and repairing cracks in boiler house welds.

With regards to its environmental policy, Longannet commissioned a flue gas desulphurisation plant (FGD) into one unit to reduce sulphur dioxide emissions by 94% in 2012 and are continuing to look at how to use this technology for the other three units onsite. Another major change in the station is the use of monitoring equipment on all the boiler houses to carefully reduce NOx emissions from the plant. Along with this the station has been improving measures to tackle boiler clinker arising from fouling in the system, as well as reducing noise, and by implementing better management systems, and transformer replacement. Looking more closely at this project, Longannet is also committed to working alongside the community and engaging with the local area and respecting the surrounding environment and its biodiversity.

The motivation for this project is to further enhance the opportunities that can be gained from the power station, by looking at how to best use some of the low-grade heat being disposed into the sea, through the canal system. In any case, a single use of some of the disposed heat from the condenser outlet will enhance the overall efficiency of the plant, and may enhance some of the areas around the site. However, a full analysis of the system will have to be carried out before any technologies or procedures can be suggested, and it is clear that in all engineering projects, there must be a balance between time, cost, and resources against the overall benefit that the system change would bring to the site or the local area. The increase in renewable energy in the UK is having a significant effect on the operation and overall use of older and more traditional methods of generation, such as that of Longannet power station. The main concern over coal fired plants is the use of finite resources, low efficiencies and green-house gas emissions, and over the next few years it is clear that the future of these power plants relies heavily on the focus of new and alternative energy. The question lies however, whether Scotland and the UK will be able to maintain a 100% supply from renewable generation and match that with the overall power demand. There is much discussion to whether new plants such as Nuclear and biomass combustion will be able to meet that of the supply from coal/gas fired power plants, and if these generation methods can be successfully matched with the unpredictable outputs from other renewable sources such as solar and wind energy.

It is clear that in order to maintain a mixture of technologies around the UK, some of the more traditional and reliable methods of power generation should be kept, and therefore there could be a window of serious opportunity for Longannet to hold its position on the energy generation map. However to do this, it is important that Longannet implements new technology and new methods into its existing system in order to maintain good operational standards as well meeting the environmental standards proposed by environmental agencies and the government. Furthermore, now that renewable technology is on the rise, Longannet may in fact be able to use this to their advantage and the project proposed will endeavour upon looking into how the energy lost through the condenser output and cooling water flume can be used to successfully recapture some of this energy before being transferred back in to the sea for re-circulation.

In relation to this project, and the motivation behind finding new and alternative methods to cooling water heat recovery, is that Longannet hopefully will have an extended life, pushing beyond 2020 and aiming towards 2030. It is clear from the Longannet station manager that in order to extend station life, the power station must change or better their environmental and operational policies. Under the achievable target banner for station environmental policy there are a few minimum standards that the staff and management hope to achieve, which sets serious motivation for this project;

- ✓ Minimise the use of resources by promoting – Reduce, Reuse and Recycle
- ✓ Optimise plant efficiency to reduce fuel consumption and minimise pollution

1.2 Details of Longannet Power Station

In order to grasp the concept of the project and how the cooling water system works it will be necessary to fully outline and understand how the station works with regards to the full system and operational procedures. The figure below shows a bird's eye image of the power plant, with some of the main features outlined.

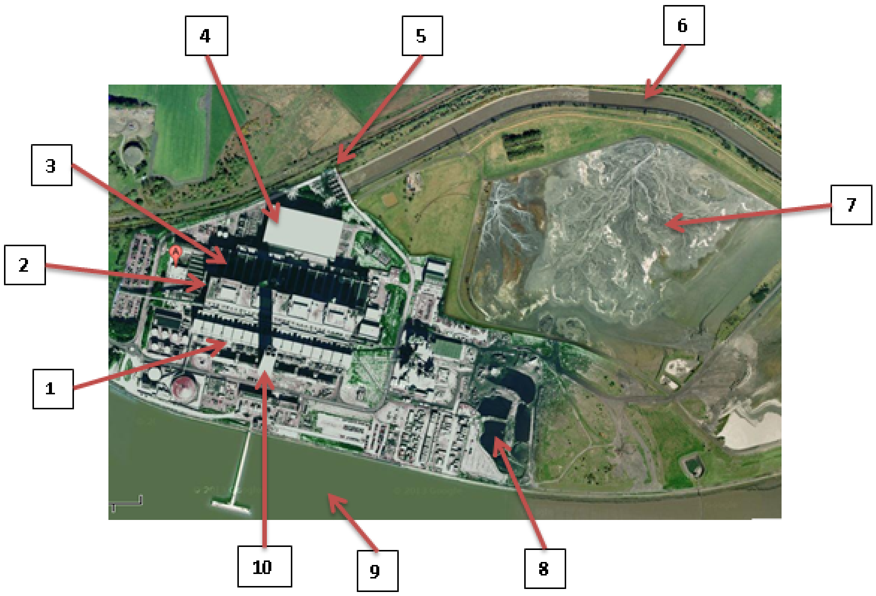


Figure 1: Photo of Longannet Power Station

1. Electrostatic precipitators
2. Boiler House
3. Turbine House
4. Transformer House
5. Cooling Water Pumps
6. Cooling Water Canal
7. Ash Lagoons
8. Settlement Ponds
9. Firth of Forth
10. Chimney Stack

The diagram below shows a basic box diagram of the inputs, processes and outputs to the power plant as well as a brief description of some of the main processes. A more detailed analysis of the site will be described fully under a working model later in the project which will allow me to achieve some of the objectives listed in the next section. It is important to show the full system to understand how the condensers and outlet are positioned in relation to the rest of the system. The cooling water output from the condensers has been highlighted in red to show the focus of the project.

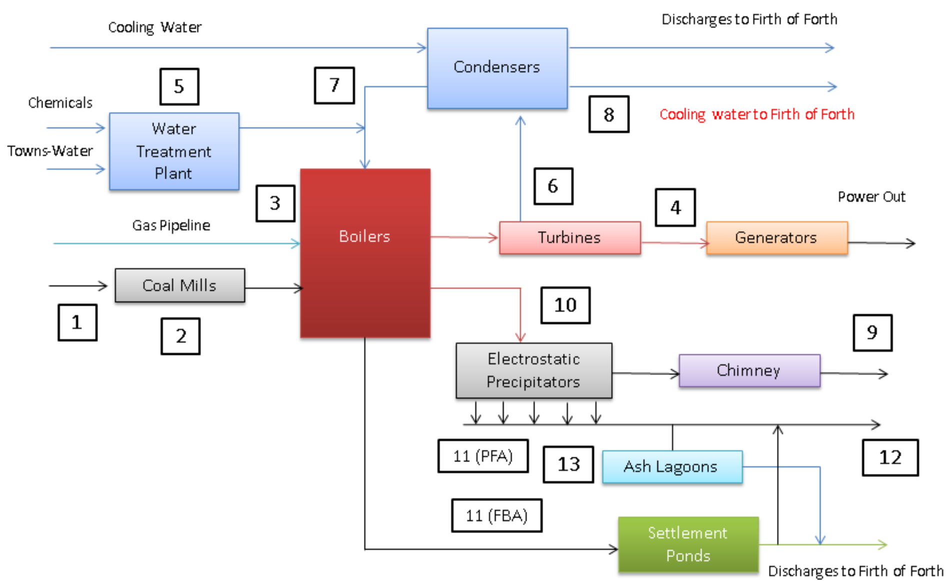


Figure 2: Diagram showing Longannet System

1) Coal is moved from a central storage location to the bunkers in the boiler house by a long conveyor system
2) Coal roller mills pulverise the coal into a fine powder and then the material is mixed with preheated air and blown into the furnaces and combusted at high temperatures
3) The site contains four boilers which are made up of a large number of water filled tubes which makes up the heat exchanger. As the hot gas from the combustion of the coal passes through the system it boils the water into tubes, thus producing steam.
4) Around 1,800 tonnes of steam an hour for every boiler is ‘super-heated’ to 568°C and then passed onto the high pressure cylinders of the turbines. The steam is passed through a cross compound turbine system and where two shafts are each coupled to separate 300MW generators.
5) Water for the steam generation comes from the towns water supply and is purified with controlled chemicals

6) The steam that leaves the turbines is transferred to the condensers where steam is converted back to water and then re-circulated back into the boiler tubes.
7) The condensers take seawater from the Firth of Forth at a rate of around 327,000 cubic meters per hour
8) The cooling water is then transferred through a piping and pumping system into a canal where it naturally cools before being put back into the Firth of Forth.
9) In the old system before any flue gas de-sulphurisation was introduced, many harmful gases were released into the atmosphere through the chimney stack such as Nitrogen oxides and sulphur dioxide.
10) The electrostatic precipitators capture dust particles from the exit gases before being released into the air. A BOFA system is being used to decrease NOx and the FGD is used to reduce SO^2 emissions
11) Two types of ash are produced where pulverised fuel ash (PFA) is captured by the electrostatic precipitators and the furnace bottom ash (FBA) is collected at the bottom of the boiler and transferred into the settlement ponds.
12) Some of the ash which is produced and captured at Longannet is then re-used to make construction products
13) The remaining ash is transferred to ash lagoons for storage.

As mentioned above the condensers and the cooling water outflow are the main interests of this project. It is clear from the figures above that the outlet of cooling water (which contains low temperature sea water) has a significant amount of heat and energy which is disposed into the canal and back into the Firth of Forth. Any development or new approach on how to recover some of this heat will not impact the operation of the power plant, as the cooling water exits the system through pumps and back into a basic outflow canal. Therefore it will be important to look at how to recapture some of this heat before going back into the sea by using some form of new system.

1.3 Aims and Objectives

Aim of the Project:

"The aim of the project is to determine the feasibility of recovering a proportion of CW heat and to propose potential applications of this heat in order to improve the overall cycle efficiency of the station."

Objectives for the Project:

1. Provide a general overview of the main operating parameters of the Longannet power station and the cooling water system

2. Provide a detailed overview of the feasibility for the recovery of a proportion of the heat contained within the CW flume. This will include an overview of the potential technologies that could be adopted considering the latest developments in heat recovery systems.

3. Provide a feasibility report on the potential use of the recovered heat to be utilised either or offsite or offsite applications.

4. Provide a recommendation as to whether Longannet should pursue any of the technologies identified in the project.

5. Carry out a review of the potential benefits of heat recovery from this system including an assessment of the costs associated with the technology including a basic assessment of the impact of initial costs and running costs.

6. Provide an overall recommendation for the recovery of a proportion of the heat lost in the cooling water system, and identify any other possible work that could be perused by Scottish Power in order to apply any of the solutions suggested.

Chapter 2: Literature Review

2.1 Low Grade Heat Recovery

Low grade heat has serious potential for recovery in the UK and around the world and this recovery and re-use of disposed heat also has the potential to reduce energy consumption and reduce emissions. Heat recovery systems are designed to conserve energy by re-using wasted heat. There are many different ways in which heat can be recovered and in this project there will be a number of combinations of technologies that will be proposed for the recovery of heat from the cooling water system in the exit canal. In any system heat recovery will reduce overall energy costs, minimise the cost and size of respected equipment for the initial process and the reduction of energy use (Industrial and Commercial Heat Recovery Systems, 1983). Most heat recovery research has been conducted around large industrial sites and for the potential for heat recovery in large commercial buildings and large housing complexes. Common heat sources include ambient air, exhaust air, lake water, river water, ground water and waste water (Kahraman, 2009). It seems wise then to understand the need for some form of heat recovery, as many of these industrial processes are subject to wasting large amounts of heat to the atmosphere or other waste streams. A study carried out by Imperial College London for the Department of Energy and Climate Change (DECC) in 2013, reviewed a number of large industrial sites in the UK for a potential of heat recovery systems. From this study, data from 73 of the largest industrial sites in the UK were collected and results showed a total 48TWh/yr. being wasted, which equated to one sixth of total energy use (Imperial College London , 2013). The UK industry consumes around 20% of the final energy consumption, where energy demand for heating in this sector is at 73% (DECC, 2011). The DECC outline that the total potential for waste heat recovery is estimated at around 10-40TWh/yr. which would in turn reduce energy consumption, increase security of supply, reduce costs and CO^2 emissions. It is clear that in this particular area, there is an opening for low grade heat recovery however there have been some other studies carried out that could be used to recover heat from hotels and other commercial buildings. For the purposes of this report I will only be looking at the recovery of heat from water sources, which will be from the cooling water canal at Longannet power station. The drive for more ground-source and water source heat pumps is that the air source heat pumps are more susceptible to temperature variations and therefore it may be possible to better achieve heat recovery through some form of water source. In an example study it was found that the temperature of waste water from restaurants, laundries and other related facilities was around 20-40°C and there are some technologies that exist that could utilise this waste heat and convert it to a much higher temperature. For example heat pump systems could be used to take some of the heat and then increase its overall temperature to that of the inlet temperatures of hot water systems in houses at 50°C.

The literature review explains some of the methods by which to recover waste heat that could be used on the Longannet power station. The review includes a detailed analysis of heat pump systems, including water source heat pumps and other methods such as the conventional organic Rankine cycle and thermoelectric systems. From the outset it is clear that the conventional use of the Rankine cycle was not suitable for the project, due to the high temperature range for the source of waste heat. However the idea of the organic Rankine cycle, which uses a fluid with a lower liquid-vapour (boiling point) temperature than that of the water-steam phase change. The graph below shows the temperature ranges of the various technologies available for low grade heat recovery. It shows a good possibility of using heat pumps as one of the solutions to low grade heat recovery at Longannet power station.

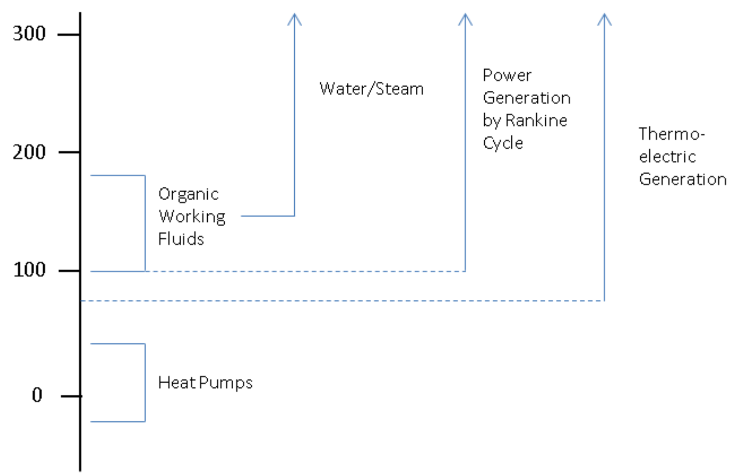


Figure 3: Temperature ranges of various technologies

The literature review also reviews the use of ammonia (not an organic fluid) as a possibility for electricity production, formally seen in Ocean Thermal Energy. This is also a possibility for recovering some of the heat at Longannet and some of these principles could be applied. The possibility of combining the cooling water into another system such as a solar thermal plant is also discussed as well as the need for waste heat resources in farming and land plantations.

2.2 Heat pumps

There is a serious potential for the use of heat pumps in recovering some heat wasted in different streams. Heat pumps have a greater potential to recover some lost heat over some of the other more conventional methods such as the Rankine cycle. As seen in figure 3, the heat pump cycle and technology is perfect for the low temperatures associated with the cooling water system at Longannet (typically around 20°C, more information provided on further chapters). There are many different types and configurations of heat pump systems, many of which have been already deployed in the UK, or are under development which is driven by financial incentives such as the Renewable Heat Premium Payment Scheme (RHPPS) and the Renewable Heat Incentive (RHI). In 2011 there were 37,000 air and ground source heat pumps installed in the UK (28,000 in the domestic sector and 8,500 in the non-domestic sector, which equated to around 0.6GWth in installed capacity and a generation level of 0.7TWh. It was outlined by the DECC (department of energy and climate change) that non-domestic heat pumps could contribute up to 22TWh by 2020; 14TWh from ground source and 9TWh from air source. (DECC, 2011). The graph below shows the deployment potential for non-domestic heat pumps up to 2020.

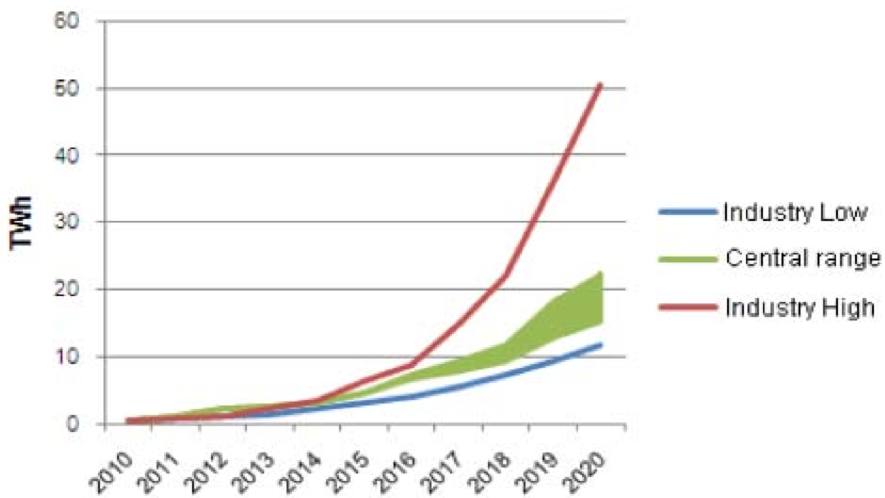


Figure 4: Deployment for Heat Pumps 2020 (DECC, 2011)

Seen in figure 4, it is clear that there is a huge potential for non-domestic heat pump systems in the UK including ground source and air source heat pumps. It is evident that this particular technology could be a possibility for industrial waste heat sources, such as that from the cooling water outlet of Longannet.

2.2.1 Basic Heat Pump Principles

Many industries have significant problems with the incapacity to use low-temperature for another purpose and in most cases this low grade waste heat is dissipated to the atmosphere and is deemed not useful energy. Of course in any engineering project, the cost and resources needed to apply a system must not exceed the benefit given by the technology. Heat pumps are devices that can accept heat from low temperature sources and produce an output of a much higher and useful temperature and in all cases needed some form of energy to run the system. Heat pumps and refrigerators are deemed to be thermodynamically equivalent however the operating temperatures are different. A refrigerator takes heat from the cold body inside the fridge and is released through a condenser at the back at temperatures in a range of 0 to -30°C. Sources of heat for heat pumps are within the range of 0-50°C, which can be found in the air, ground water or waste heat streams from industrial sites. The heat pumps works by taking this heat and upgrading it to a much higher temperature usually ranging between 50-90°C. The difference between the two systems is that a heat pump would not be used to extract heat to maintain a cold climate but would be used to extract heat to an already warm climate. (Crook, 1994)

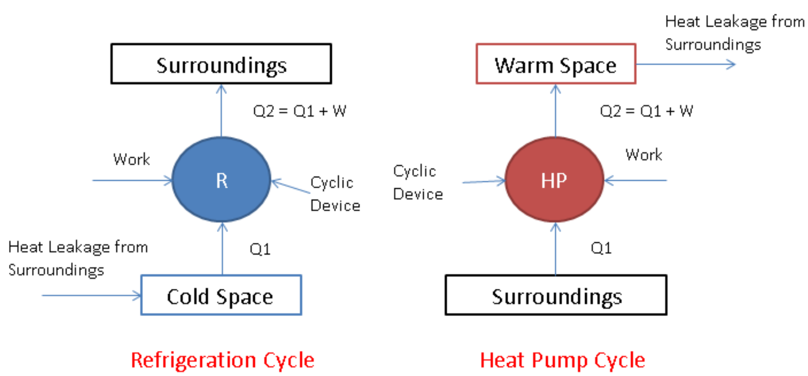


Figure 5: Refrigeration vs. Heat pump cycles

The vapour refrigeration cycle is based on trying to maintain a cold region lower than that of the surroundings which includes the Carnot vapour refrigeration cycle. This cycle is the reverse of the Carnot vapour power cycle. The figure below shows the respected cold region, components of the cycle, warm region and the T-S diagram for this process. The cycle begins by circulating a refrigerant through all the components, where processes are internally reversible. The refrigerant enters the evaporator as a two phase liquid-vapour mixture, and during this process some of the refrigerant changes phase from liquid to vapour as a result of the heat being transferred from the cold region. The temperature and pressure of the refrigerant remains constant while passing through the evaporator. The refrigerant is then compressed adiabatically in the compressor leaving as a saturated vapour. During this process, the temperature increases from Tc to Th and the pressure also increases. The refrigerant passes from the compressor to the condenser, where it changes phase from saturated vapour to saturated liquid as a result of heat transfer to the region at Th (the temperature and pressure remains constant over the condenser. The refrigerant returns to the state at the inlet of the evaporator by expanding adiabatically through a turbine, where the pressure decreases and the temperature returns from Th to Tc.

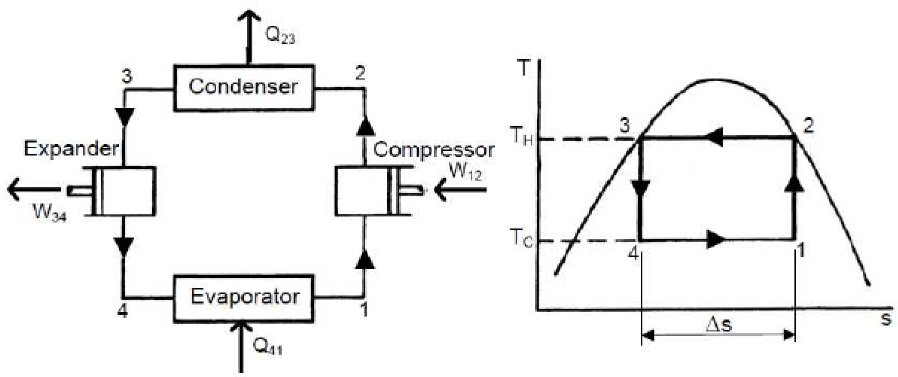


Figure 6: Carnot Vapour Refrigeration Cycle (Tuohy, 2013)

Heat pumps are however based on a more practical vapour compression cycle which has some different features to that shown in figure 6. For example, this process can have problems associated with “wet compression” where there are liquid droplets in the liquid vapour mixture entering the compressor (which can result in damage). Another impracticality of the system shown above is that expansion process from saturated liquid state 3 to low quality; two phase liquid vapour mixture state 4. The expansion produces a small amount of work compared with that of the input to the compressor and the work output of the turbine would be further lowered by low efficiencies operating at this level. So to alleviate these problems and reduce the costs associated with turbines, it is replaced with an expansion valve, where the fluid goes under isentropic expansion. This process allows for dry compression and is called a vapour compression refrigeration system, which can be seen in the figure below.

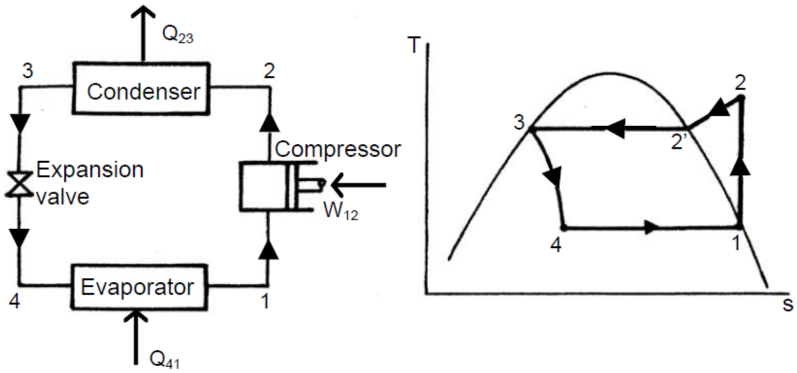


Figure 7: Vapour Compression Refrigeration System (Tuohy, 2013)

Heat pumps can be split into two main types; vapour compression and absorption cycle. The two types of heat pumps use the same principles however the compression of the vapour is different. Vapour compression can be seen in figure 7 and describes the use of a compressor to increase the temperature and pressure of the working fluid. There are two main vapour compression designs; the most popular uses an electric motor to drive the compressor and the other uses heat output from an engine cooling system. (Crook, 1994) Another major factor that influences heat pump compression design is the working fluid, as in many cases CFCs have been used, however this has led to some problems with regards to the environment and so there have been some developments in more environmentally friendly working fluids and the use of natural working fluids, however there are some design considerations and implications of using new and developed working fluids (IEA Heat Pump Centre , 2013).

The compression cycle heat pump uses a complex mechanical device for the compressor and there are certain limits to the maximum operating temperatures of the system, typically around 100-120C. The absorption cycle is used to overcome this problem and can be used for much higher output temperatures. In an absorption cycle system, the evaporated vapour is not compressed directly but absorbed into a fluid at the vapours low evaporation pressure. The fluid containing the vapour is pressurised with a pump to the correct condensing pressure. At this point external heat is applied to boil off the absorbed vapour which is then put through a condenser, where heat can be dissipated and then finally returned back to the evaporator through an expansion valve (which returns it to normal operating pressure). Figure 8 shows the working components of the closed loop system within the absorption heat pump.

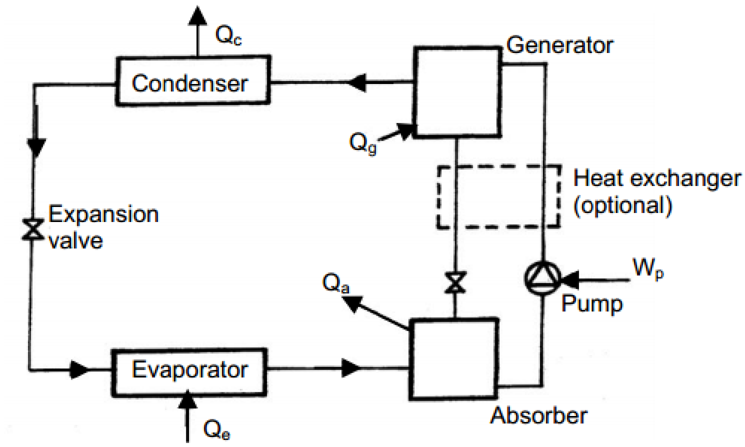


Figure 8: The Absorption Cycle (Tuohy, 2013)

As mentioned above the absorption cycle and the vapour compression cycle are variations of the same working principle, there are key differences to the way the working fluid is compressed. Mechanical energy is used for the compression cycle, where as a heat input is needed to recapture the vapour from the working fluid. For absorption cycles, the heat output is a lower grade than that of the heat input to the generator; however the any source of heat can be used to generate the vapour. The absorption of vapour by the fluid is an exothermic reaction, where in compression systems all of the heat output is from the condenser and in absorption cycles heat output is from the condenser and the absorption components. Under the heat pump compression cycle, it is possible to use a multi-stage system that achieves higher efficiencies, mainly due to have more than one compression cycle in the system. There are two main types of multi-stage systems; cascade and compound. The first basic multi-stage compression system is shown in the figure below (compound) which has a high and low pressure compressor as well as a stage of cooling. With the basic one compressor system, there is much higher pressure ratio across the compressor and therefore the work input to run the compressor is higher, thus reducing the efficiency of the component. If the system is split between two stages with some form of inter-cooling, the overall compressor work input is reduced, as well as the discharge temperature while the efficiency is increased.

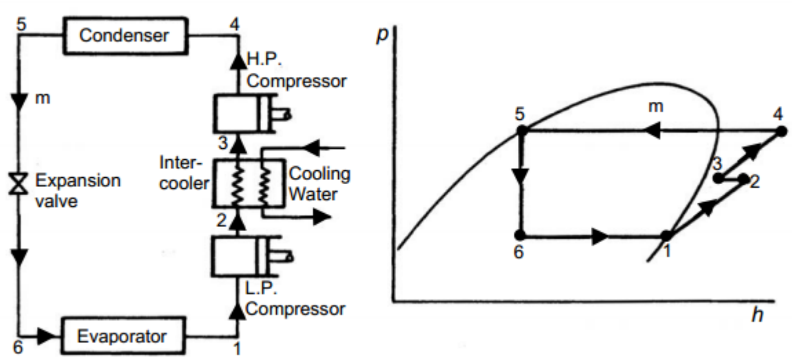


Figure 9: Multi-stage Heat Pump (Compound)

The cascade method uses a flash intercooler, where liquid refrigerant from the condenser is used as the cooling method for multi stage cooling system. The expansion of the fluid now happens in two expansion values, where the gas discharged from the low pressure compressor is passed through the refrigerant fluid through a direct contact system. Figure 10 shows the outlay of the system, where at point 7 a saturated liquid is created, where by the refrigerating effect per unit mass is increased. The cascade system therefore has two separate refrigeration cycles at low and high evaporation temperatures, where the heat is exchanged through a direct contact heat exchanger.

2.2.2 Heat Exchangers for Heat pump Systems

In any heat exchange mechanism, it is important to analyse the different types of heat exchangers available for the heat pump system. An example of a heat exchanger is the Slimjim flat plate exchanger being used in various geothermal projects (shown in figure 11 and 12). Heat exchangers are used to transfer heat from fluid to another; common use of a heat exchanger is in power plants, where condensers (heat exchangers) condense the incoming stream from the turbines, reducing it back to a useful form and recirculated back into the boiler house. There are many types of heat exchangers available, typically shell and tube exchangers, double pipe, cross flow and flat plate exchangers. The double pipe heat exchanger consists of two tubes, with the inner tube running inside the outer tube carrying one fluid. The outer tube also carries a fluid to which heat can be transferred, either by a parallel or counter flow arrangement. It should be noted for much larger systems, multiple double pipe heat exchangers and be used in one unit to maximise the amount of heat transfer between the two fluids. In any heat exchanger arrangement, including that of the double pipe, the performance of heat transfer is based on these principles arrangements; (Janna, 2009)

- ✓ The total amount of heat transferred between the two fluids
- ✓ The outlet temperature of both fluids after passing through the pipe network
- ✓ The required area of heat exchange
- ✓ Fluid flow rates inside both pipes
- ✓ Diameters of the pipes
- ✓ Inlet temperatures of the fluids heat exchange fluids entering the system

The diagram below shows the typical outlay of a double pipe heat exchanger, with relevant equation to calculate the overall heat transfer coefficient.

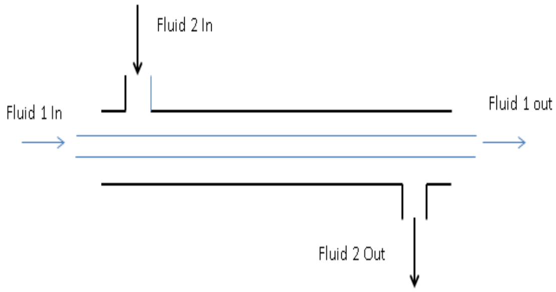


Figure 10: Double pipe Heat Exchanger

$$\frac{1}{U} = \frac{1}{hi\left(\frac{Ai}{Ao}\right)} + \frac{Do}{2k} \quad \ln\frac{Do}{Di} + \frac{1}{ho}$$

$$= \frac{1}{U} = \frac{1}{hio} + \frac{1}{ho}$$

Double-pipe heat exchangers are useful for heat transfer over low flow rates and reasonable temperature differences, however when heat exchange between fast flowing fluids is needed, a shell and tube exchanger is a solution to this problem, which can cope with high heat transfer rates. The exchanger is made up of one main large diameter pipe (the shell), which has a number of smaller tubes integrated inside. One fluid is put through the shell pipe, while another fluid is passed through the smaller inner tubes, whereby the heat transfer process can take place. It is then possible to have a multitude of shell passes with x number of tubes to increase the rate of heat transfer between the two fluids; however it is obvious that this will increase the surface area and overall size of the exchanger. The shell and tube exchanger is a simple mechanism for heat transfer and contains these basic components; (Janna, 2009)

- ✓ The shell which contains the inlet and outlet nozzles,
- ✓ The inner tubes
- ✓ The tube sheets which hold the tubes in place.
- ✓ Channel covers
- ✓ Transverse baffles for directing flow of the shell fluid
- ✓ Baffle Spacers for securing the baffles in place

The shells are usually made from steel or iron material, however it should be noted that for an open loop scheme, corrosion resistant materials should be used. The tubes inside the shell are constructed using standard metals such as copper and can be orientated in various ways inside the shell. The baffles are an important addition to the exchanger and are situated inside the shell to control the flow of the fluid and further increase the heat transfer between the two fluids. The spacing of the baffles will control the speed at which the fluid passes over the tubes. It is possible to enhance a shell and tube exchanger by increasing the amount of times the fluid in the tubes passes through one shell pass. In simple terms in a single tube pass exchanger it is hard to maintain a high fluid velocity (high Reynolds number, Nusselt number and film coefficient). Control of the fluid in different systems is controlled by flow dividers at the end channels. (Janna, 2009)

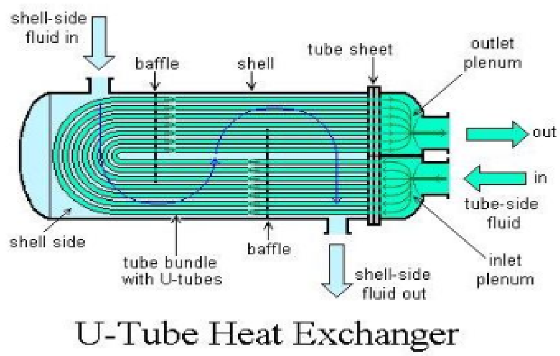


Figure 11: U-Tube Shell and Tube Exchanger (Bengston, 2010)

The plate exchanger is also another exchanger that should be considered for heat transfer purposes and an example of this can be seen in the section above in figure 11 and 12, which displays a modern version of a flat plate heat exchanger. However, it must be noted that the Slim Jim flat plate exchanger is suited for the purpose of ground water sources, where in the case of a shell and tube exchanger, it is mostly used for condensation and evaporation purposes, similar to that used in heat pump systems. This flat plate exchanger is also a possibility for heat pump components. The flat plate has some advantages over the shell and tube heat exchanger. For the same heat transfer rate, the plate exchanger is smaller than the shell and tube exchanger. In the case of protection against corrosion, it is important that special resistive materials are used, and due to the flat plate using less surface area, the costs associated are reduced. However in the case of using normal materials, the shell and tube is cheaper than a flat plate. The shell and tube is better suited to high temperatures and high pressures due to the limits on gaskets on flat plate systems. The figure below shows a typical liquid to liquid flat plate heat exchanger. (Reiter, 1983)

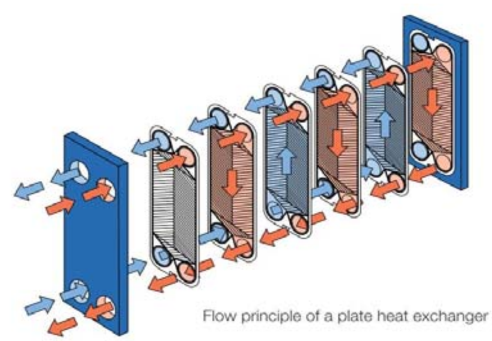


Figure 12: Flat Plate Heat Exchanger (Energy Today , 2012)

2.2.3 Heat transfer basics for heat exchangers

In order to fully evaluate the workings of a heat exchanger, it is necessary to outline the basic theoretical calculations for further analysis. The overall heat transfer coefficient is the pinnacle of any heat exchanger analysis. When fluids pass through a heat exchanger and are separated by a single tube and where the radiation effects are neglected, the overall heat transfer coefficient ($U = W/m^2.k$) can be measured by looking at the inner or outer surface area. This is written as;

$$\frac{1}{U_1} = \frac{1}{h_1} + \frac{r_1}{k}\ln\frac{r_2}{r_1} + \frac{r_1}{r_2 h_2}$$

$$\frac{1}{U_2} = \frac{r_2}{r_1 h_1} + \frac{r_2}{k}\ln\frac{r_2}{r_1} + \frac{1}{h_2}$$

U = Overall heat Transfer coefficient ($W/m^2.k$)
h = Heat Transfer coefficient ($W/m^2.k$)
r = radius of pipe
k = thermal conductivity (W/m.k)

In the case of thinned walled tubes, the conduction resistance and wall thickness effects can be neglected and is therefore expressed as;

$$\frac{1}{U} = \frac{1}{h_1} + \frac{1}{h_2}$$

During operation the surfaces of the heat exchanger can be subject to fouling and corrosion, leaving a film or scale on the surface, which in turn increases the resistance to heat transfer and decreases the performance. Fouling factors can be introduced to compensate for the increase in thermal resistance across the exchanger. This is expressed as;

$$\frac{1}{U_1} = \frac{1}{h_1} + R'_{f1} + \frac{r_1}{k}\ln\frac{r_2}{r_1} + R'_{f2}\frac{r_1}{r_2} + \frac{r_1}{r_2 h_2}$$

$$\frac{1}{U_2} = \frac{r_2}{r_1 h_1} + R'_{f1}\frac{r_2}{r_1} + \frac{r_2}{k}\ln\frac{r_2}{r_1} + R'_{f2} + \frac{1}{h_2}$$

For calculation of the heat transfer coefficient under various conditions, the Nusselt number can be calculated using various parameters. For natural convection the Nusselt number is expressed as the function of Rayleigh number and Prandtl number, while forced convection is expressed as the function of Reynolds number and Prandtl number. The Nusselt number is expressed as;

$$Nu = \frac{h.l}{k}$$

For forced convection heat transfer over cylinders in the heat exchanger can be expressed as;

$$Nussult\ number = 0.023\, Re^{0.8}\, \Pr 0.4 \qquad Re = \frac{DV\rho}{\mu} \qquad \Pr = \frac{C_P.\mu}{k}$$

D = diameter of pipe (m)
V = velocity through the pipe (m/s)
p = density of the fluid (kg/m³)
u = viscosity (kg/m.s)
k = thermal conductivity (W/m.k)

As another example for calculating the Nusselt number to work out the heat transfer coefficient h, to find the overall heat transfer coefficient is shown below. The natural convection over a flat plate is expressed as;

$$Gr = \frac{D^3 \rho^2 g\, \Delta T\, \beta}{\mu^2} \qquad (Ra = Gr\, Pr)$$

$$Nu = \left\{ 0.60 + \frac{0.387\, Ra^{1/6}}{[1 + (0.559/Pr)^{9/16}]^{8/27}} \right\}^2$$

D = diameter of pipe (m)
g = gravity (m/s²)
p = density of the fluid (kg/m³)
u = dynamic viscosity (kg/m.s)
B = Volumetric expansion coefficient

Once the overall U value has been calculated, it is possible then to calculate the total rate of heat transfer across the two fluids in the exchanger. Under no phase change conditions with specific heats are at a constant in a concentric tube, the total rate of heat transfer between the two fluids can be written as;

$$Q = \dot{m}_{f1} Cp_1 (T_{f1(i)} - T_{f1(o)})$$

$$Q = \dot{m}_{f2} Cp_2 (T_{f2(o)} - T_{f2(i)})$$

However, since the temperature will change at different points across the heat exchanger, the equation for total rate of heat transfer can be written as;

$$Q = UA\Delta T_m$$

This expresses the log mean temperature difference across the exchanger and can be written for a counter flow arrangement as the following;

$$\Delta T_m = \frac{\Delta T_b - \Delta T_a}{ln(\Delta T_b / \Delta T_a)} \qquad Q = UA\frac{\Delta T_b - \Delta T_a}{ln(\Delta T_b / \Delta T_a)}$$

2.3 Surface Water Heat Pumps

For the purposes of this project, the cooling canal for the Longannet could be assessed as a fully functioning river, as a water source for heat pumps. Water source heat pump systems are a viable and low cost ground source heat pump (GSHP) option. Lakes, streams and bays are all considered as a good source of heat, and where possible heat sinks and heat pump systems could be employed. (Kavanaugh, 1997) Air source heat pumps have been the most popular, as the source is widely available and the technology can be deployed very easily, however the capacity and performance is quite low due to changes in the climate, both in summer and winter months for heating and cooling purposes. Air source heat pumps cannot provide suitable output temperatures in colder climates during the winter months and therefore become very inefficient and unsuitable. Furthermore, there are new ways being discovered that can effectively use some heat from waste streams in industries and other non-commercial buildings. A heat pump in this instance can be used to effectively recover and upgrade the low temperature water source to a much high output temperature, which could be used for various applications (Kahraman, 2009). The energy consumption for hot water in commercial buildings is deemed lower than that for HVAC. The condensing temperature of a heat pump is around 50°C, where the average temperature of hot water for domestic purposes is about 45°C. Therefore using heat pumps systems is an efficient way to utilise waste heat for domestic hot water systems. (Kahraman, 2009). There have been a number of comprehensive studies carried out regarding the utilisation of waste heat using heat pump systems. (Details of these reports and findings can be seen in future chapters). To fully understand how surface water heat pump systems work, the various types and combinations must be analysed.

2.3.1 Closed Loop Systems

First we must analyse the two main types of surface water heat pumps; closed loop and open loop systems. In closed loop systems, a type of heat exchanger can be placed in a body of water and heat can be extracted and transferred to a fluid medium inside the exchanger. In this case a water-air source heat pump is connected to the exchanger, and is used to upgrade the heat extracted to that needed for cooling or heating inside a building. Figure 10 shows the configuration of a closed loop ground source heat pump system. In this particular system a central loop pump provides the fluid medium from a set of loose bundle high-density polyethylene coils to a number of heat pumps inside the building.

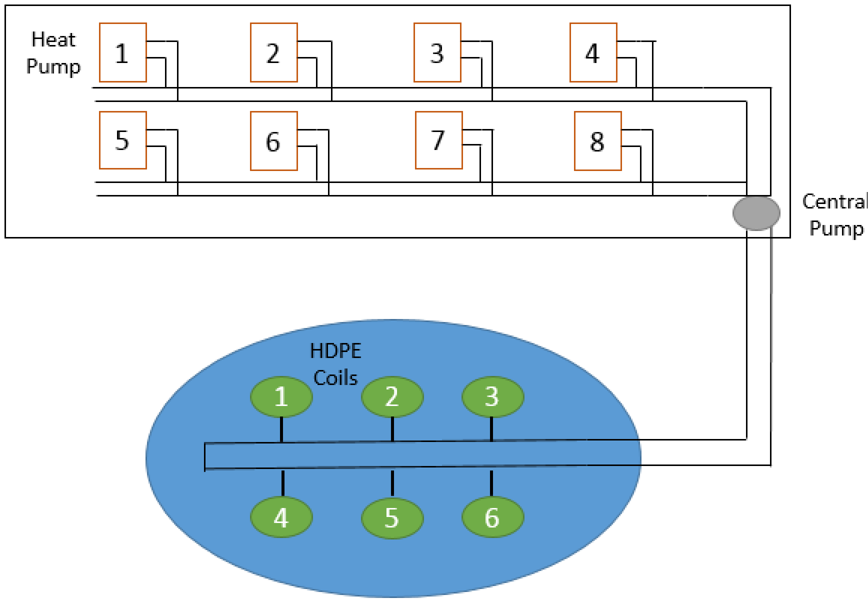


Figure 13: Closed Loop Surface Water System

For surface water systems, there are many factors that require a detailed analysis in order to fully understand how much heat can be extracted from a certain stream. In terms of ground source heat pumps, there are some constraints to the amount of heat that can be extracted, such as the amount of heat exchange surface in the ground and the amount of heat flux lost through the surrounding surface. David Banks (Banks, 2012) also describes that in closed loop systems the stream of water must have sufficient surface area or large water through flow in order to have adequate heat exchange and that there is also a good area used for the heat exchanger to maintain good efficiencies. It should be mentioned that the low thermal conductivity of water does not have a serious effect on the heat exchange, as convection in the water streams also has a significant part to play in the heat transfer process (from natural flow and convection cells) and the thermal performance will be mainly bound to the efficiency of the heat exchanger and not by the properties of the water. There are two main types of heat exchanger that can be used in lake based or river stream systems; coils or flat plate heat exchangers. Again, in these water sources it is necessary to make sure that;

- That the correct amount of heat exchange area is installed
- That there is adequate heat exchange efficiency
- In the above case, to make sure that convection and advection can happen around the heat exchange area

- And to finally make sure that there is enough through flow and consistency of water being provided to the heat exchangers

As mentioned above, in closed loop systems the fluid is circulated around the heat exchange element which is fully submerged in the water stream. There a few types of coil systems which can make use of cheap and favourable material such as Polyethylene (PE), High density polyethylene (HDPE) or Polyvinyl chloride. In some cases copper tubing has been successfully implemented as a heat exchange material. (Kavanaugh, 1997). Banks describes different means by which to install closed loop circuits of HDPE in lake based systems.

1. Parallel type '**slinkies**' can be used on the bed of a lake or stream. They have good thermal efficiency but are hard to install.
2. **Loose coil** bundles can be placed on the bottom of a lake and can be attached to a frame or wire cage.
3. **Coils** can also be placed on a raft type system, where the raft can be positioned with the coils and then sunk to the bottom of the link.

Another typical heat exchanger used in water source systems is a flat plate heat exchanger (which can be seen in the figure below). A typical flat plate heat exchanger that has been used for some UK projects include the New Lanark conservation site, which used a 'Slimjim' flat plate exchanger on a large scale. The total cost of the system was £144,000 and was installed instead of PE coils due to the risk of the tubing being caught in the turbine and destroyed. In this project three 3.6m × 1.2 flat plate heat exchangers were submerged into the incoming water flow. The output of the heat pump provides heating for the visitor centre and costs have been reduced by 40% (The Green Blue). This system can be easily installed and more plates can be added when needed, and provides a potential higher overall benefit than PE tubing systems. (Supply, 2014). In typical heat transfer mechanisms flat plate exchangers are favoured over other methods as they are easier to maintain, more compact and have a higher value for overall heat transfer coefficient.

Figure 15: Typical Slim Jim Heat Exchanger

Figure 14: Kings Mill Hospital (Slim Jim Installation)

2.3.2 Open Loop Systems

As mentioned above, the other type of surface water heat pumps are open-loop systems, where water is pumped from a body of water through an intermediate heat exchanger. In this case the closed piping loop connects the heat pump system to the other part of the heat exchanger. The heat exchangers used in this process are similar to those used for groundwater heat pumps. A filter is also used in order to prevent any debris coming into the heat pump. (Kavanaugh, 1997) The water pumped through the exchanger is then returned back to the water source at the later stage in the cycle. Kavanaugh explains that open systems are restricted for use in warmer climates or for buildings in colder climates with cooling loads or small heating loads only. In open loop systems there is always a risk of frosting on the exchanger and also that the body of water maintains enough water through the process to stop temperatures dropping below 42F. For Open loop systems, the lake water temperature variations are very difficult to model and require much more complex modelling than groundwater counterparts. The diagram below shows the typical outlay of an open-loop system. The heat pumps inside the building use a circulating fluid through the exchanger, which is driven by a secondary loop pump. The water from the source is pumped through a filter screen and then carried out the piping network to the building.

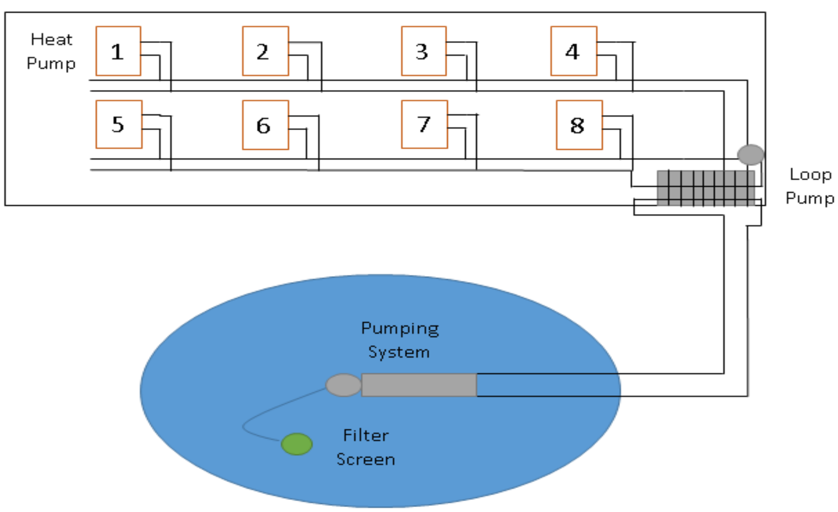


Figure 16: Surface Water Heat Pumps - Open Loop

The points below outline some of the major advantages and disadvantages of using open-source systems over closed loop systems; (Kavanaugh, 1997)

- ✓ There is a greater heating and cooling capacity as the water will be directly affected by the season temperatures. In the summer the water source will be much higher, and losses associated with the exchange to a fluid medium in a closed system are not incurred in the open loop system
- ✓ It is possible to use water located deeper in a lake for direct cooling purposes and precooling of return air
- ✓ Open systems can be modelled to withhold disturbance on the natural temperature of the water source by rejecting some water warmer closer to the surface
- × Fouling of the heat exchanger from open water source
- × System efficiency can be low, as large pumps are needed when there is a large elevation head between the water and the heat pump.
- × It is possible for very low temperatures that the system may have to be switched off, as the costs associated with the pumps outweigh that of the benefits of the system. For temperatures close or just above 0°C the heat pump may be susceptible to freezing.

The points below outline some of the advantages and disadvantages of closed loop systems over open loop systems; (Kavanaugh, 1997)

- ✓ Reduced fouling through the circulation of clean water through the heat pump system, where conditions of the water does not affect the components inside the system and the piping network
- ✓ Less pump power is required for the system. In an open system two pumps are needed to circulate both the water from the source and then a secondary pump to circulate the working fluid around the heat pumps. In closed loop systems there is no need to allow for elevation head between the water surface and the pumps.
- ✓ Closed loop systems can be used when water conditions fall below 4°C
- × The overall performance of the heat pump is reduced because of the circulation of the fluid inside the closed loop degrades the temperature of the incoming water through heat transfer
- × Damage to the coils or heat exchange mechanism from the condition of the water. Condition of certain materials may degrade overtime.

2.3.3 Loop Materials and Coil design for Closed Loop Systems

As mentioned above the closed loop system is based on a number of coils or flat plates being situated in the source i.e. the body of water for heat transfer to take place. There are various methods and designs by which to install these systems into the body of water but more importantly the selection of material being used for the design is highly important. In most cases copper is the material of choice with high thermal conductivity, however copper can be subject to corrosion (may be particularly bad for sea water outlet at Longannet). It is therefore important to look at other suitable materials for heat transfer. (Banks, 2012) For plastic material, polyethene has the highest thermal conductivity and is durable and is suitable for this particular application, where medium density and high density polyethene would be appropriate for these systems. It should be noted that pressures inside the pipe network must be considered, however for horizontal closed loops, the pressures on the network would be much less than that of vertical systems. The pipes should also have some form of UV protection when located on the water surface. One other major advantage of using plastic piping is that it is very flexible and can be easily installed using various pipe diameters. When different diameter of piping is used, it is important to use consider the surface area, hydraulic resistances and heat exchange capacity for loop systems. The table below shows some the thermal conductivities for some possible loop materials that could be used for closed loop systems.

Material	Thermal Conductivity (WmK)
High Density Polyethene (HDPE)	0.45
Polyethene	0.42
Medium Density Polyethene (MDPE	0.4
PolyPropene (PP)	0.22
Polybutene	0.22
Polyvinyl Chloride (PVC)	0.23
Steel	16-54
Copper	390-401

Table 1: Thermal Conductivities of Materials (Banks, 2012)

It is important when using coils for heat transfer in closed loop systems that we consider the correct amount of material, the correct diameter of piping, a sufficient amount of coils or loops and that the coils are located in a reasonable location in the water. The different types of plastic piping have been mentioned in the previous section; either as a loose bundle coil (secured with weights) or a spread ‘slinky’ coil. It is important that the correct amount of coil length is used for either cooling or heating purposes, where the length can be designed around the approach temperature. The figure table below shows the minimum required flow rate for non-laminar flow for a number of liquids. It can be assumed for selection of tubing that the with flow rates that produce a higher Reynolds number will have little impact on heat transfer and the coil length, as most thermal resistance is in the wall of the pipe and on the outside surface, if the flow is non-laminar. (Kavanaugh, 1997)

Fluid (% Weight)	t = 30 °F				t = 50 °F			
	Diameter of Pipe				Diameter of Pipe			
	0.75 in.	**1 in**	**1.25 in**	**1.5 in**	**0.75 in.**	**1 in**	**1.25 in**	**1.5 in**
20% Ethanol	3.8	4.8	6	6.9	2.6	3.2	4	4.6
20% Eth. Glycol	2.5	3.1	3.9	4.5	1.8	2.2	2.8	3.1
20% Methanol	2.9	3.6	4.5	5.2	2	2.5	3.1	3.5
20% Prop. Glycol	3.4	4.2	5.4	6.1	2.3	2.8	3.6	4.1
Water	0	0	0	0	1.1	1.4	1.7	2

Table 2: Minimum Required Flow Rate (gpm) for Nonlaminar Flow Re>3000 (Kavanaugh, 1997)

2.4 Ocean Thermal Energy and Solar Applications

This section explains briefly the use of organic Rankine cycles for ocean thermal energy technology and the possibility of solar integration. There is a potential for the use of the technology associated with ocean thermal energy for the Longannet power station circulating water. Some studies have been carried out previously by the University of Strathclyde about the use of ocean thermal technology on the cooling water outlet of a power station. Results and the conclusions of these reports are given in this section. Ocean thermal energy is a means by which to recover the heat from the surface of a particular body of water i.e. the sea and transfer some of this heat to an organic Rankine cycle, typically using an ammonia working fluid for electricity production. There is much investigation and consideration for the recovery of low grade heat from both solar and ocean thermal sources. The OTEC technology uses the oceans natural temperature difference to drive a power cycle. It should be mentioned that in order for the technology to work effectively, a temperature difference of no less than 20°C should be used to produce a significant amount of power. (Wang, 2010) The process uses a simple but effective Rankine cycle components; to include an evaporator, turbine, condenser and circulating pump. The figure below shows the component structure and outline with respect to the solar temperature effect on the surface water in comparison with the lower temperatures found further down in the water source.

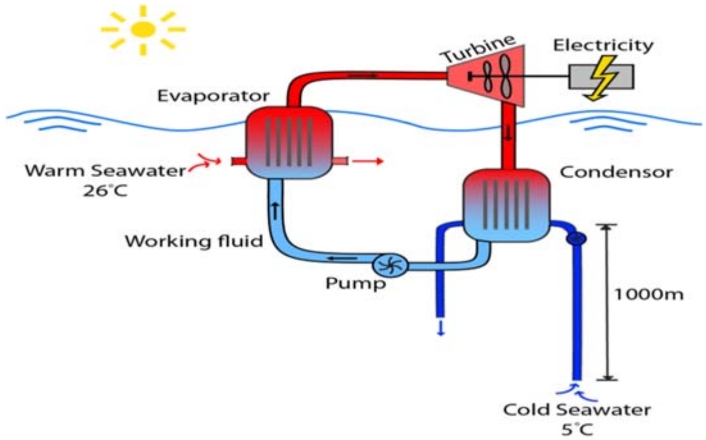


Figure 17: Closed loop OTEC Technology (Delft University of Technology , 2014)

There are two main types of OTEC systems; open cycle and closed cycle. In the closed cycle system, the working fluid is conserved within the cycle and recirculated back to the evaporator following the condenser. In an open loop system the working fluid is vented after it is processed through the system, where warm water from the sea would be pumped directly into a chamber, where the pressure is reduced so that the water can brought to boiling point. The low pressure steam is then passed through a turbo-generator and then condensed by direct cold water contact. The closed loop system using an ammonia working fluid would typically pass warm sea water into an evaporator, where the working fluid would boil to create a vapour that can be passed through a turbine to expand. The vapour returns to its original state through a condenser, where cold water from the sea at a much lower temperature is passed through, which is then passed onto the evaporator to restart the cycle (Avery, 1994).

Work carried out by a University of Strathclyde team, showed that the power production from an OTEC cycle using the water outlet from the condensers was possible for two power stations; Longannet and a combined cycle power plant in India. They found that in the Indian power station there was a net power increase of 1.56MW, which gave an overall increase of 0.42% thermal efficiency to the overall combined cycle. Likewise for Longannet, a net power increase of 4.2MW was achieved, giving an overall increase of 0.27% to the power plant. However for this study, a few assumptions were made for the inlet and outlet temperatures of the cooling water and condenser circulating water, and are therefore not viable for this study. The information provided shows hypothetically what the power output would be under some favourable conditions, not realistic to Longannet power station. In order to achieve a suitable power output and one that gives a positive net power output the cooling water for the condenser was calculated at 4°C, which is typical of only winter conditions. As the outlet temperature of the cooling water is around 20°C, the temperature difference was found to not be suitable using the tool provided by the research team, as the pumping power required for a higher flow rate of circulating water was too large in comparison with the overall output from the turbine and therefore subjecting to a power loss across the system.

Chapter 3: A Review of Heat Pumps and Water Heaters

3.1 Working Fluids for Heat Pump Systems

One of the design parameters for any heat pump system is the selection of the working fluid. There are a few issues concerning the use of some of the refrigerants being use for heat pumps. The first main issue that must be addressed is the effect that the fluid has on the environment, as leakage of certain chemicals is deemed to have an effect on the stratospheric ozone. The refrigerant also has an effect on the performance and operation of the heat pump cycle. There are two main types of hydrocarbons that are used as refrigerants in heat pump systems; HCFC's and HFC's which warm the climate and have an adverse effect on the ozone (Harvey, 2006). Under the Montreal Protocol, there is a phase out plan set for the reduction of the used of CFCs and HCFCs for developed and industrialised countries. It is important that the use of new working fluids have the same potential as existing fluids, and that there is no effect on the cost and reliability of the heat pump system. However, it should be mentioned that energy efficiency of a heat pump is not solely down to the working fluid being used, and heat pump design should also be considered (Heat Pump Centre, 2014). The table below shows some of the typical working fluids used for vapour compression cycles.

Refrigerant	R-404a	R-407	R-410a	R-507	R-134a	R-290	R-717
Components	44% R125 52% R143a 4% R134a	23% R125 25% R125 52%R134 a	50% R32 50%R125	50% R125 50% R143a	R-134a	Propane	NH3
Temperature at 25 bar °C	53	55-59	41	52	78	68.3	58
Temperature at 1 bar °C	-47 to -17	-37 to -44	-52	-47	-26	-42.1	-33.3
Critical Temperature °C	74.4	86.4	71.8	71	100.6	96.7	130

Table 3: Typical Refrigerants for Heat Pumps (Harvey, 2006)

Most of the refrigerants being used contain a mixture of one or more fluids and the temperature of the evaporator and the condenser depends on the heat flux to or from these components. When the outside air is warm in comparison to the evaporator, the heat flux will be large, which would in turn increase the temperature of the evaporator and reduce the overall heat flux. As the incoming air cools as it comes into contact with the evaporator (heat transfer), the heat flux will decrease and will then decrease the temperature of the evaporator, which will in turn try to maintain the original heat flux value. The change in temperature of the evaporator over time is called the temperature glide. Using a pure refrigerant, with a constant evaporator temperature, the differential will decrease as the air flows and cools, which puts a limit on heat transfer. In order to cope with this, a range of working fluids can be used to increase heat transfer and minimise losses through temperature differentials in the system, thereby increasing COP (Harvey, 2006). There are a number of natural working fluids that exist and could be used for heat pump systems that have a substantial potential for use in modern systems. One of the major benefits of these fluids is that they have minimal ozone depletion and global warming potential, and could provide a long term solution to reducing the need for CFCs and HCFCs. Some of the natural working fluids for heat pump systems are given in the points below; (Harvey, 2006)

- **Ammonia** – Is commonly used in medium to large industrial refrigeration plants and will be a good fluid for high temperature purposes. Some problems include flammability and toxicity. Existing heat pumps have reached a condensing temperature between 58°C to 78°C. Ammonia cannot be used with copper materials and have not been introduced into high temperature industrial heat pumps due to the lack of high pressure compressors.
- **Hydrocarbons** – Hydrocarbons are highly flammable but are thermodynamically acceptable and can be used with a range of material. Some of the most common fluids used for heat pumps are a mixture of propane and propylene and hydrocarbons are typically used in domestic refrigeration and small heat pumps.
- **Water** – Water is a good working fluid for high temperature industrial heat pumps and is non-flammable and non-toxic. The typical working fluid temperatures range from 80 - 150°C and can be used for absorption and compression cycles. The major disadvantage with water is the low volumetric heat capacity.
- **CO^2 –** CO^2 has a good potential for heat pump systems as it is non-toxic, non-flammable and can be used with a variety of materials. The volumetric refrigeration capacity is high in comparison, which in turn reduces the pressure over the system. One disadvantage with CO^2 is that it has a low COP value.

3.2 The Potential for CO^2 as the Working Fluid for District Heating

CO^2 is under much investigation as a suitable working fluid for heat pump compression cycles and therefore much research into super critical carbon dioxide. Supercritical carbon dioxide will have distinctive thermo physical properties close to the critical point unlike that of sub-critical conditions. These physical changes have an adverse effect on the temperature profile of the heat exchanger and the levels of heat transfer in the heat pump. The increase of CO^2 in heat pumps is driven over the environmental concerns of existing working fluids. Some of the major benefits of carbon dioxide as a working fluid is given below; (Chen, 2006)

- ✓ It is inexpensive and is widely available, natural working fluid
- ✓ It is more chemically stable and much more reliable than other refrigerants
- ✓ It is non-toxic and non-flammable
- ✓ Due to higher working pressures the heat pump is more compact

The main benefit of using CO^2 is that the critical temperature is very low in comparison with other working fluids: 31.1°C. This temperature is lower than common condenser temperatures and therefore heat rejection must occur above the critical temperature and critical pressure (73.8bar) and heat absorption must occur below these critical values; this process is called the transcritical cycle. The condenser is replaced by a gas cooler, where the temperature and the pressure are reduced however remain above the critical line, and therefore no phase change occurs before the expansion valve.

For CO^2 heat pumps the heat rejection temperature is separate from that of the heat rejection pressure, and in other heat pump systems (using other working fluids) the COP will decrease as both pressure and temperature increase (Harvey, 2006). The operating pressure of a CO^2 heat pump is between 80-135Bar and temperature can rise up to 90°C, with an evaporator temperature as low as -6.4°C at pressures of 30-35 Bar. (White, 2002). It is clear that using CO^2 as a working fluid for heat pump systems is ideal for hot water systems and for district heating networks where higher temperatures are needed, above that of traditional heat pumps, which typically have condenser temperatures of around 55°C.

It should be mentioned that even though CO^2 alone is a greenhouse gas, the comparison between the amounts used or leaked to the atmosphere in comparison with that released to the environment through conventional power, is minimal (Harvey, 2006). The major drive for using carbon dioxide as a refrigerant is the fact that it has a good potential for replacing these traditional working fluid heat pump systems and reducing the overall use of CFCs and HCFCs (Wilson, 2013). The table below is taken from a major supplier of CO^2 heat pumps (Ecocute) and shows the relative environmental values for other refrigerants against CO^2.

Refrigerant	CO^2	R-134A Tetrafluoroethane	R-407C Mixture HFCs	R-410C
Ozone Layer Depletion Potential	0	0	0	0
Global Warming Potential	1	1300	1600	1900

Table 4: Global Warming Potential (Mayekawa, 2014)

One of the ideal CO^2 heat pump systems that are on the market is well suited to the purposes of hot water heat recovery systems and also for district hot water networks. There is a serious potential for Longannet to provide a source for a district hot water network through the outflow from Longannet. However to understand the current potential in heat pump systems, it is necessary to look at the current heat pump systems on the market that can be used for low source inlet and high temperature outlet flows for hot water networks. It is clear from literature that there is sufficient evidence to look at heat pump domestic hot water systems. However, the outlet temperatures given in some studies such as that of (Kahraman, 2009) are considerably lower than stated for CO^2 water source heat pumps. The Ecocute heat pump (Mayekawa, Japan) claims to be the first commercial heat pup system that can cool and heat at the same time and can heat water up to +90°C. Some of the benefits of the eco cute heat pump are given below; (constructed from technical data sheet)

- ✓ **Environmentally Friendly** – uses a natural source and has no damaging effects on the atmosphere and contains no combustion process and therefore eliminates the release of harmful gases to the air
- ✓ **High COP value –** The Company claims that the system can produce a COP of 8.0 which is much higher than that of other heat pump systems (typically around 3-4)
- ✓ **Low Operation cost –** The system can refrigerate chilled water and ice thermal storage at night, makes use of night time energy
- ✓ **Suitability –** the heat pump can be used for medium-large scale industrial and commercial purposes and can maintain a water supply of 22,000L at 90°C.
- ✓ **Continual circulating heat –** the pump can operate with inlet temperatures of 65°C and 90°C outlet, which prevents bacterial growth in the supply water.

The diagram below shows the typical outlay of the Ecocute system for hot water production that could be used for district heating purposes.

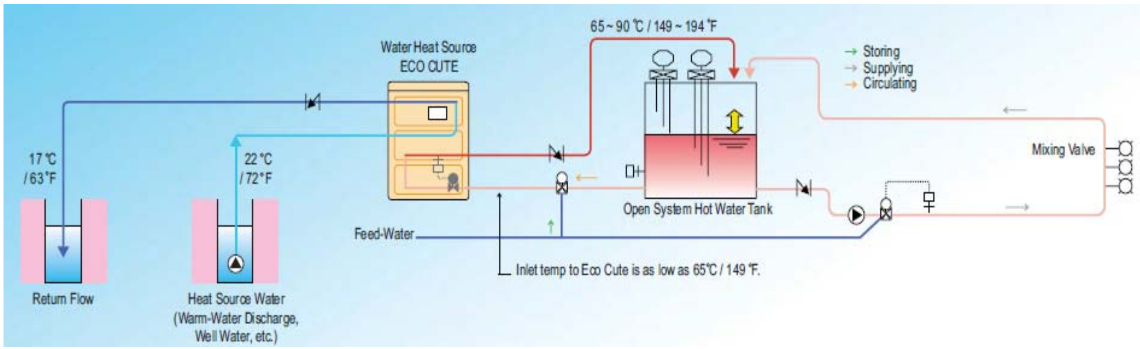


Figure 18: Ecocute Heat Pump - Heat Recovery (Mayekawa, 2014)

3.3 Heat Pump Water Heating System

For this investigation it is also important to look at some reports on using heat pump systems for waste water as the heat source. The section above describes some of the existing studies for the use of heat pumps in water heating systems. These studies include the use of waste water as a heat source for heat pump systems that can upgrade the heat to normal domestic temperatures. Kahraman explains that there have been certain studies carried out regarding this subject, where hot water production has been analysed using air, solar and ground sources. The most comprehensive and relatable study was carried out by Dogan (Dogan, 1999) who analysed a water-water heat pump system using waste water from a hotel in Antalya. In this case the water taken from the condenser was used during the summer months to provide hot water to the hotel and during the winter months, water from the sea was used for heating and hot water production. This study found an improvement of cooling and water production to be at 16% and 75%, respectively. Baek (Baek, 2005) designed a heat pump system that used waste water from a hotel sauna as a heat source for meeting hot water demand from the hotel. The performance of the heat pump was measured at 4.8 and could meet the requirements for hot water demand on weekdays.

It is clear that there is a huge potential for water source heat pumps in waste water heat recovery, however there is a serious lack of study and systems in place that use waste water recovery from commercial and domestic buildings (Kahraman, 2009). There is a possibility that the Longannet cooling water flume could provide an essential supply of hot water to the local area or for the power station itself. In all heat pump systems (including hot water source systems) it is important that the source can be properly utilised and the coefficient of performance (the balance of work input against the heat output gained) depends on many factors, such as the temperature of the water source, the output temperature of useful heat, the working fluid used, the state and operation of the components and the temperature of the evaporator. (Hepbasli, 2008). The heat pump water heater system works off the same principles of a vapour compression cycle for heat pumps, where the output heat from the condenser is transferred to a hot water cylinder, which would be typically used for hot water services in the domestic or commercial sector. However in the study carried out by Hepbasli, the system was based on incoming ambient air and upgrading this heat to suitable temperatures for domestic hot water. The system works on a basic principle that when temperatures become too low, the heat pump is switched off and replaced by a backup electrical system (Franco, 2010) . The figure below shows the outlay of HPWH system.

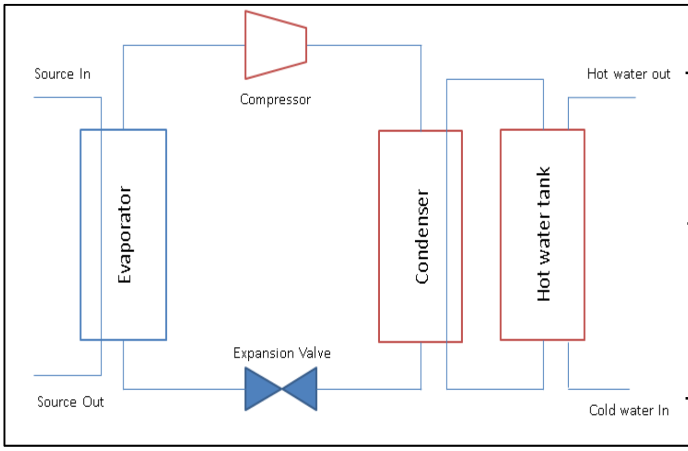


Figure 20: HPWH Cycle

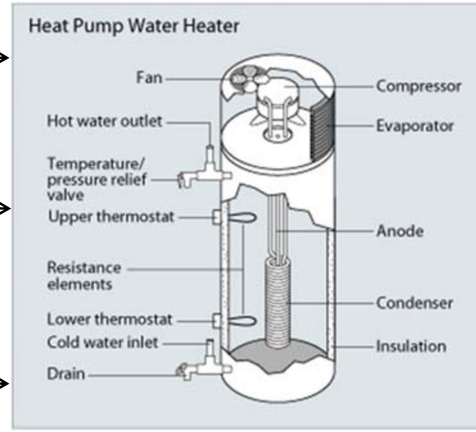


Figure 19: HPWH Tank (Energy, 2012)

3.3.1 Review of the performance of a heat pump using waste water as a heat source

This section shows the results and outcomes from a study carried out using typical waste water temperatures. This study outlines that there is a serious need for new forms of energy at both the large and small scale to be integrated with the existing technologies that are in place. It is ideal that a heat pump system could be used, which would reduce the emissions on domestic and commercial buildings while reducing the need for conventional supply. Decreasing the energy consumption with regards to the production of hot water may reduce the overall demand for housing, and therefore reduce the reliability of older and more expensive systems e.g. electric heating. It should be mentioned that this study has significant relevance to the cooling flume of Longannet power station, as it can be treated as a normal waste flow of a low temperature water source (however flowrate of water will be significantly higher). There is a potential for recovered and upgraded water (if economically and technically viable) to be used in conjunction with existing hot water systems, however before this can be evaluated, the results of this report highlights the function of heat pump cycles for this purpose. The figure below shows the outlay of the relevant heat pump water heater cycle and follows the same principles as a vapour compression cycle. Likewise, the main components are the evaporator, condenser, evaporator and expansion valve. The refrigerant R134a (tertafluoroethane) was circulated through the system. A plate type heat exchanger was used for both the evaporator and the condenser. The system included two water circuits with two storage tanks, with relevant pumps to circulate the fluid. Data was collected at three different temperatures (20°C, 30°C, and 40°C) and at different volumetric flow rates. Temperatures were recorded at the output of the condenser. Results from this study will be highly applicable to the cooling water outflow of Longannet.

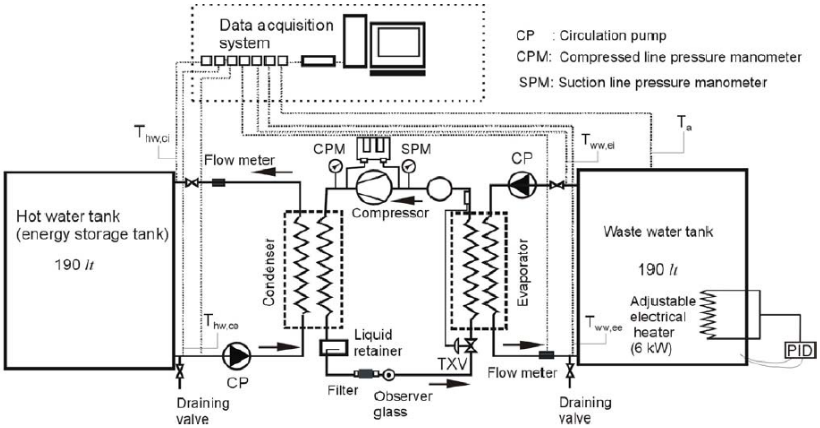


Figure 21: Heat Pump Hot Water System Set up (Kahraman, 2009)

Firstly, various mass flow rates were selected for the circulation pumps and results found that the temperature difference at the input and output of the condenser was much higher for the lowest mass flow rate e.g. at 20°C the temperature difference was 7.5°C at the lowest mass flow and 3.4°C at the highest mass flow rate. Similar trends were recorded for the 30°C and 40°C temperatures. The main findings of this report was the increase of water temperature inside the hot water tank at the lowest flow rate, where the temperatures reached 49.4°C, 51°C and 55.6°C for values of 20°C, 30°C and 40°C, respectively. It was concluded that this system would be good for domestic hot water systems, and there a viable solution to hot water recovery. However the system was measured on a COP basis, which would detail the amount of work input to the system against the amount of heat supplied to the hot water tank. One issue was the increase in pressure over time at the three temperatures, from 5.5bar to 12.8bar, 5.5 to 14.1, and 5.5 to 15.2bar for waste temperatures of 20°C, 30°C and 40°C, respectively. Cop values were recorded at 3.34, 3.51 and 3.77 to 1.87, 1.83 and 1.77 for 20C, 30C and 40C waste water temperatures respectively. The graph below shows the decrease of COP values over the slowest mass flow rate. Results show that the system changes the water temperature quite significantly, and that the highest COP value was at the highest mass flow rate with 40°C waste temperature. The results show in this case, the heat pump is a viable solution to hot water production over that of original heating supply. The only slight issue with the system is that efficiency and COP values both decrease when the temperature of the water in the storage tank reaches 50°C.

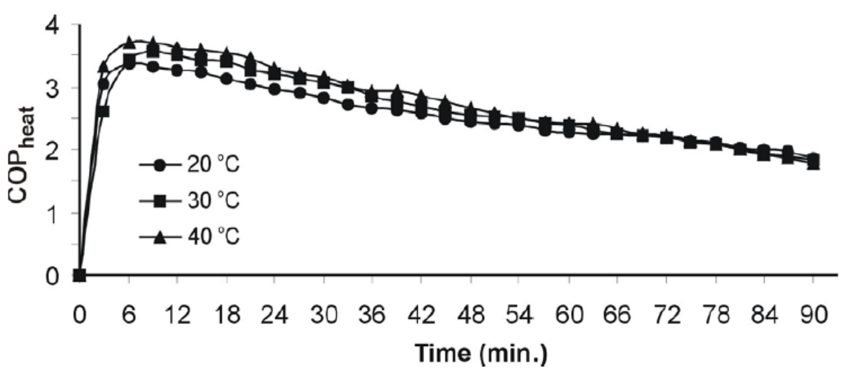


Figure 22: COP Values on CP1 Flow Rate (Kahraman, 2009)

3.4 Conventional vs. Transcritical Heat Pumps

In order to fully access the possibility of recovering some of the heat from the circulating water in the power station, an assessment and model must be created in order to look at how much heat can be recovered and if this heat can be used for a domestic hot water cycle. It is clear from the assessment that conventional heat pump systems are not suitable for high temperature applications such as district heating/water networks. From the literature review it is evident that there will be a significant change in heat pump systems, both water and air source, and that the availability of CO^2 heat pumps for domestic hot water systems will be on the increase in the near future. As discussed above, there is a serious market for the Ecocute heat pumps, manufactured by Sanyo and the company provides some reliable and important information regarding the production of hot water. However this data does not include a retrofit with a domestic housing and a domestic hot water system. The CO^2 heat pump is specifically good for DHW systems, as they have high efficiencies and a suitable range of temperatures between the working fluid and the water in the gas cooler. G. Lorentzen was the first researcher to re-use CO^2 as a working fluid in order to eliminate the use of HFCs and HCFCs in existing heat pumps. The CO^2 heat pump cycle can be referred as a standard transcritical cycle; known as the Lorentzen cycle. The carbon dioxide transcritical cycle describes the absorption of heat at a constant temperature at sub-critical pressure and the release of heat at a 'gliding temperature' at super-critical pressure. The figure below shows a phase change diagram with the critical point at 31.1°C and 1,067psia (73.15bar).

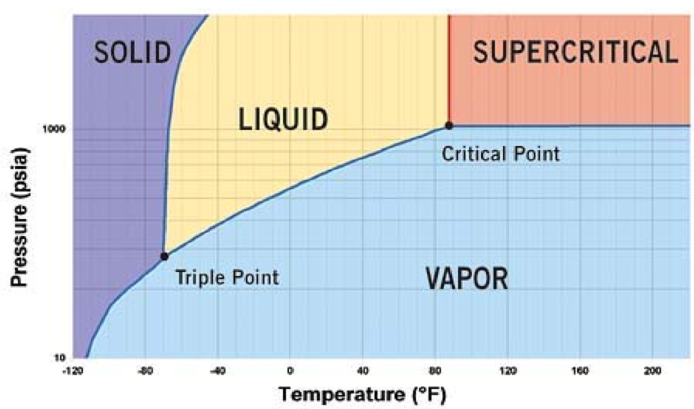


Figure 23: Phase Change Diagram - R744 (ACHR News, 2004)

In a normal heat pump using conventional refrigerants (sub-critical cycle) the working fluid passes through the processes (evaporation, compression, condensation, expansion) in the sub-critical region (below the critical point). In the case of the transcritical cycle with CO^2 as the refrigerant, the heat rejected occurs above the critical point. There is no condensation process in the transcritical cycle where temperature decreases at all points in the process, which means that the component is replaced by a gas cooler system. In the sub-critical cycle the temperature stays constant during the heat rejection process. The pressure-enthalpy diagrams for both a sub-critical cycle and transcritical cycle are shown below.

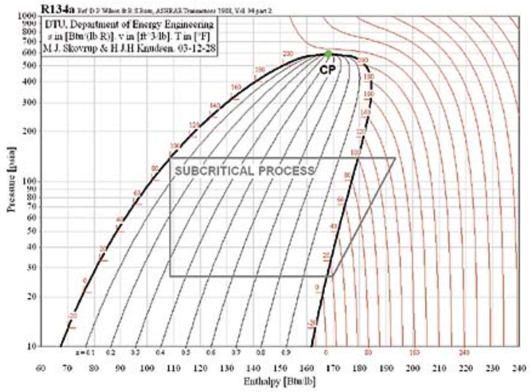


Figure 24: R134 Subcritical Process

Figure 25: R744 Transcritical Process

The standard cycle for heat pumps, when heat is given off and taken at constant pressure and constant temperature is called the reverse Carnot cycle. In the transcritical cycle, heat is absorbed at constant temperature at a sub-critical pressure and rejected at gliding temperature and the supercritical pressure stage. The diagrams below describe the ideal Lorentzen cycle as the reference cycle for an ideal cycle for heat pumps and the real Lorentzen cycle.

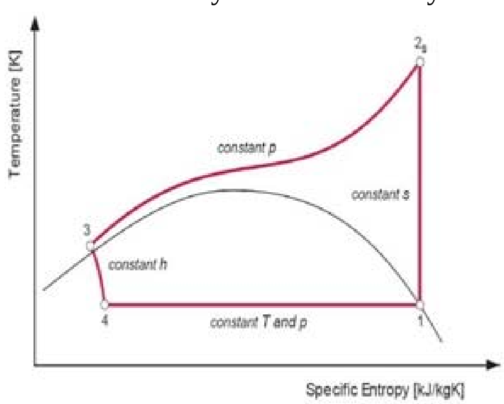


Figure 26: Ideal Lorentzen Cycle

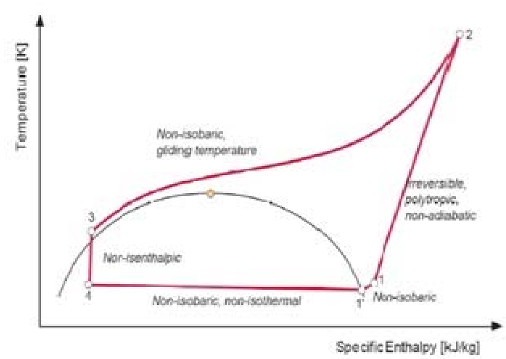


Figure 27: Real Lorentzen Cycle

Cycle process T-S Diagram:

- 4 – 1:Heat absorption at constant subcritical temperature/pressure
- 1 – 2s: isentropic compression to supercritical pressure
- 2s – 3:Heat rejection at constant pressure and gliding temperature
- 3 – 4:Isenthalpic (adiabatic) expansion

Cycle process T-H Diagram:

- 4 – 1’:Non-isobaric heat absorption
- 1’ – 1:Non-isobaric superheating of the suction gas
- 1 – 2:Irreversible polytrophic (non-adiabatic) compression to supercritical pressure
- 2 – 3:Non-isobaric supercritical heat rejection (gliding temperature)
- 3 – 4:Non-isenthalpic (non-adiabatic) expansion

In the transcritical cycle heat pump using CO^2 as the refrigerant, the heat from the source incoming (water/air) is absorbed by the refrigerant in the evaporator, where the working fluid is converted into a vapour. The vapour is passed to the compressor to be compressed to a known value above that of the critical pressure, and this heat increase in the fluid is then passed onto the gas-cooler where the heat gained is rejected to the passing fluid in the heat exchanger by the temperature glide. The working fluid is then passed to an expansion device where pressure is reduced below the critical point and back into the evaporator to repeat the cycle. The temperature glide at the gas cooler makes the CO^2 heat pump cycle favourable for constant water heating process and suitable for DHW systems.

3.4.1 Variable designs for CO^2 domestic Hot water systems

The previous section describes some of the research and results regarding standard hot water systems using conventional working fluids. It is therefore necessary to look at the various designs available for CO^2 heat pump systems supplying hot water to a standard domestic hot water system. For this project, the idea of using the heated water for a district heating scheme is still a viable solution to the Longannet circulating water problem. However in order to fully evaluate this function, a basic CO^2 heat pump cycle for a standard domestic hot water cycle will have to be modelled. This assessment will allow an analysis of the various parameters and functions of the system, to gain a reasonable COP value with respectable output temperatures from the gas cooler. It should be mentioned that the idea of water heating has been based around air-water heat pump systems. There has been much research into various designs for hot water systems such as that of Neksa et al, however most systems are based on single stage units with low pressure receivers, suction has heat exchanger and a tube in tube heat exchanger. The figure below shows a basic outlay of a simple CO^2 water heater.

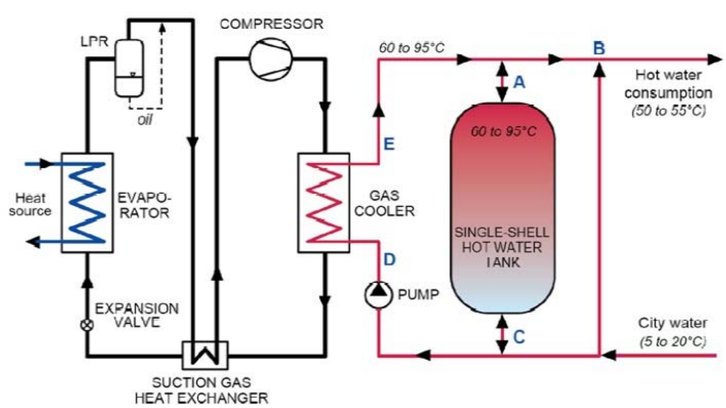


Figure 28: Simple Heat Pump Water Heater with Single Tank (Hjerkinn, 2007)

The water heater system is made up of two heat exchangers, a low pressure inlet valve and hot water tank that receives water. Water is taken from the top of the tank at point A which is typically around 60-95°C and is mixed with cold water, where hot water consumption is typically around 50-55°C. The water is replaced by a normal water inlet into the bottom of the tank, which is then fed through the gas cooler to be heated from around 5-20°C to the 60-95°C. A system pump is used to circulate the water from D to E, across the gas cooler. The experimental study from Neska (1998) (using a typical system shown above) showed promising results. This study is of particular interest for this project, as the source of heat was a water/glycol solution which was fed from a pipe network to the evaporator. The system was based upon multiple hot water tanks, with the option of the heated water leaving the gas cooler, to be transferred straight to a hot water pipe network or fed into the hot water tanks. The nominal heat output from this system was measured at 50kW. The figure below shows the outlay of the system design.

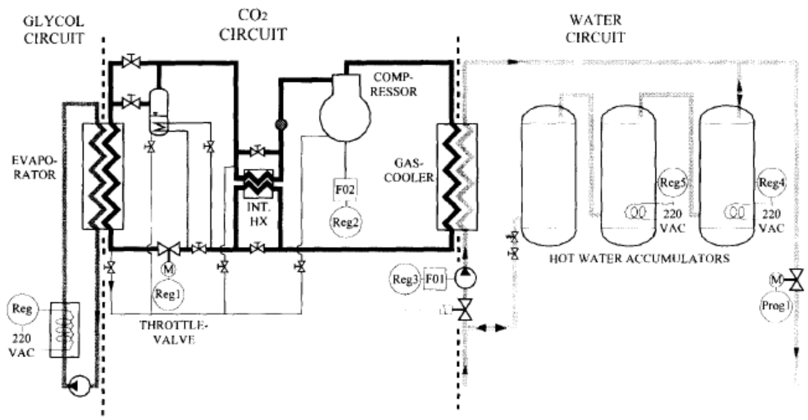


Figure 29: Prototype System Design (Neska, 1998)

The results showed that CO^2 is a suitable working fluid for heat pump systems for tap water temperatures. It was found that energy consumption can be reduced by 75% compared with conventional heating systems, with a supply of 60°C when ambient air is the source. It was also found that the heat pump could provide temperatures of up to 90°C, and efficient compression and good heat transfer characteristics contributed to high COP values. These results prove that a CO^2 heat pump is an ideal replacement for traditional heat pump systems that are restricted to temperatures below 55°C. The prototype experiment achieved a heating COP of 4.3, when heating tap water from 9°C to 60°C, at an evaporation temperature of 0°C. Even at high hot water output temperatures system efficiency was still maintained at 3.6 for 80°C output water temperatures. (Neska, 1998).

The graphs below show some of the relevant outputs from the study of this report. The figures show the varying COP values with a change in the evaporating temperature with a fixed output water temperature of 60°C, as well as a set evaporating temperature with respect to COP values vs. output water temperature. Figure 44 shows an increased COP value, for an increasing evaporating temperature with at hot water temperature at 60°C (suitable for tap water purposes). Figure 45 shows a slight decrease in COP value from around 4.2 to 3.6 for an increase of 20°C in the outlet water temperature (at 0°C evaporation temperature).

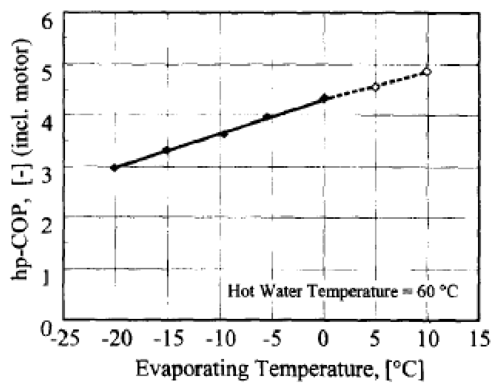


Figure 31: COP vs. Varying Evaporator Temperature

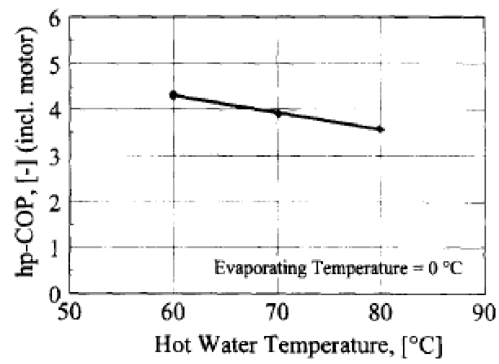


Figure 30: COP vs. Varying Hot Water Temperature

3.5 Evaluation of CO^2 Heat pumps for Domestic Hot Water Purposes

From the evaluation above, it is clear that the use of a CO^2 heat pump system is a favourable option for low grade heat recovery. It should be mentioned that research into the development has been minimal and it seems that most development has been around the Ecocute system. It also seems that there has been no significant study into the use of CO^2 heat pumps for use with any power plant or energy system as large as Longannet. In order to calculate the various input and output conditions for a CO^2 heat pump and to work out if a heat pump could produce suitable temperatures to be used for a district heating system, a study into one single heat pump compression cycle will be needed. Once these results have been established, it will then be possible to evaluate if a series of heat pump systems could be used to meet the demand profile for one of the three areas noted in the demand analysis section. A further and deeper analysis into the demand profile of certain buildings and occupancy levels will also need to be carried out. A detailed demand analysis will result in finding out typical house demand profiles with regards to hot water storage and the amount of energy required for hot water over various times of the day. An essential requirement of the CO^2 heat pump will be to analyse the COP value and maintain this value at a high level, which would be in this case the ratio of the heat given off at the gas cooler to the work input to the compressor. The pressure-enthalpy diagram below describes how the COP value can be calculated through a simple CO^2 transcritical cycle.

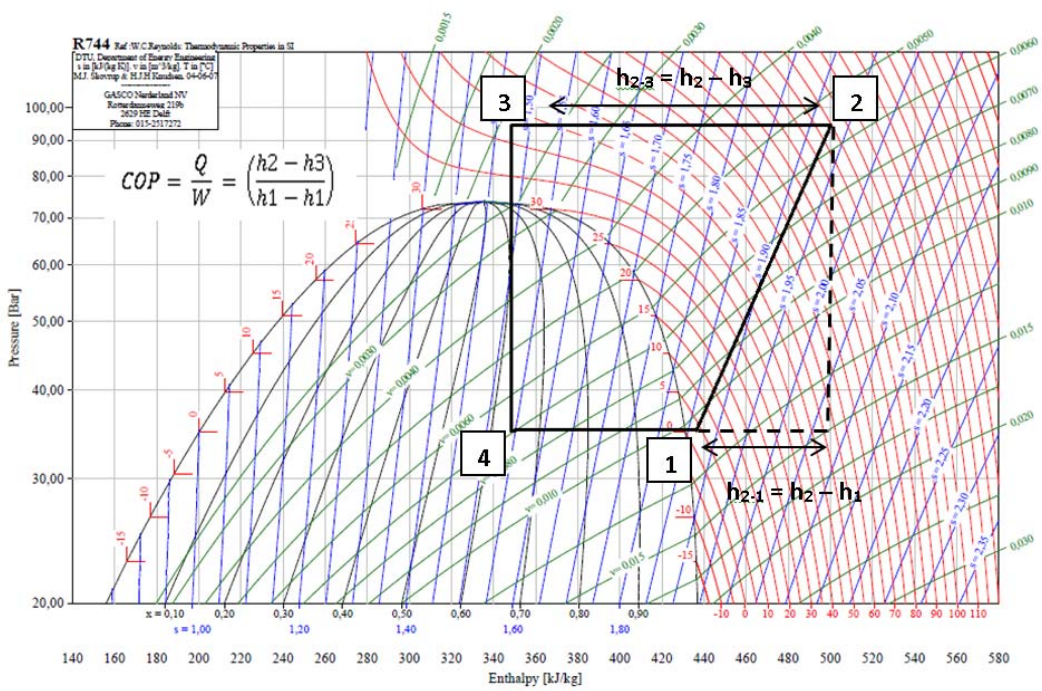
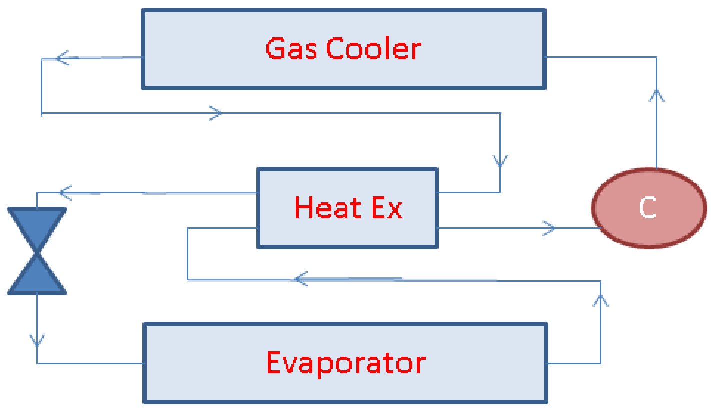


Figure 32: P-h Chart for simple CO^2 Transitional cycle (DTU, 2007)

In order to increase the cycle efficiency and the COP value for the heat pump, there are some simple methods by which to introduce additional components to the system. For example an internal heat exchanger is a very simple component that can be integrated into the heat pump cycle. In a study by researchers G. Lorentzen and Pettersen, results showed an improvement of Cop value by an internal heat exchanger. This was discovered by a way of reducing the throttling loss across the system by cooling the refrigerant before throttling. The diagram of the cycle is shown below and describes high temperature leaving gas leaving the gas cooler, where it is then subcooled before entering at the evaporator pressure, by the low temperature vapour leaving the evaporator. The basic principle is that the temperature of the refrigerant will be reduced through the heat exchanger before entering the expansion valve, by the outgoing low temperature vapour from the evaporator (Kim, 2005).



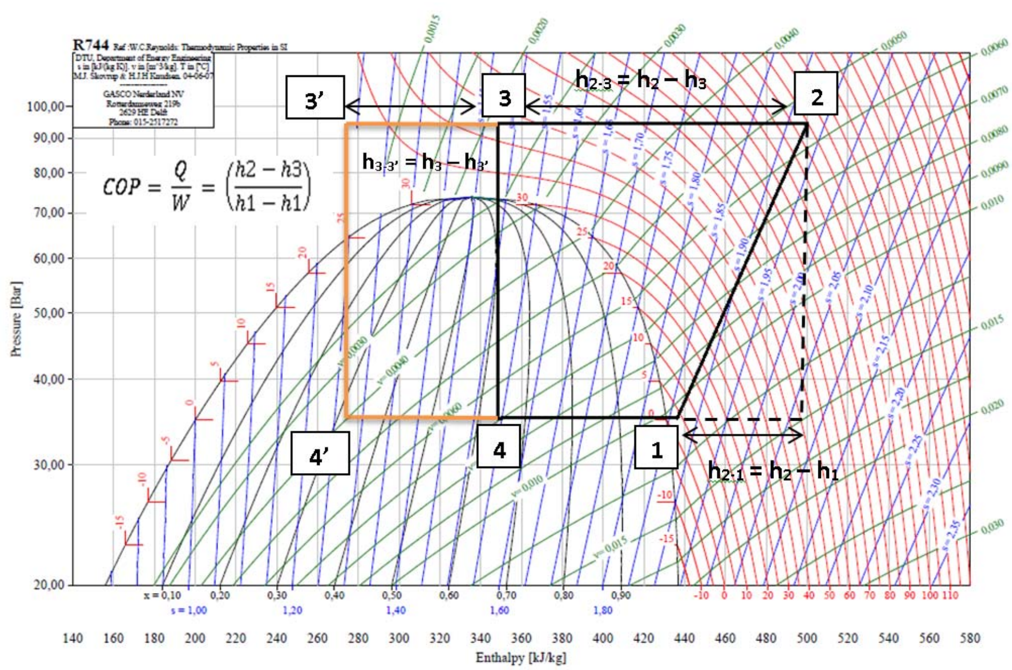


Figure 33; P-h Chart for CO² Transitional cycle with internal heat exchanger (DTU, 2007)

It is necessary to then make sure that there is a large temperature range across the gas cooler where the heat is rejected. This will mean that the there is a large enthalpy difference between the CO^2 in the gas cooler and the temperature of the CO^2 before being throttled. The outlet temperature in a gas cooler is determined by the following factors.

1. **The CO^2 mass flow rate**;
   - The efficiency of the compressor
   - Swept Volume of the compressor and RPM
   - The suction pressure and temperature
2. **The discharge temperature from the compressor**;
   - Suction pressure and temperature
   - High end pressure
   - Isentropic efficiency and heat loss from compressor
3. **The high side pressure**
4. **Design of gas cooler**
5. **Type and characteristics of fluids to be heated**
   - Inlet temperatures
   - CP values

Depending on the design of the district network and the selection of the area in which the hot water will be provided and the amount of heat pump systems to be used, the most significant factor in heat pump design will be the return temperature of the CO^2 as it passes through the gas cooler to be recirculated back to the evaporator. The diagram below displays an example multiple system that could be used as a possible design for a district network used at Longannet power station, using multiple hot water tanks as well as the possibility of using multiple heat pumps, to increase the rate of output water with respect to demand.

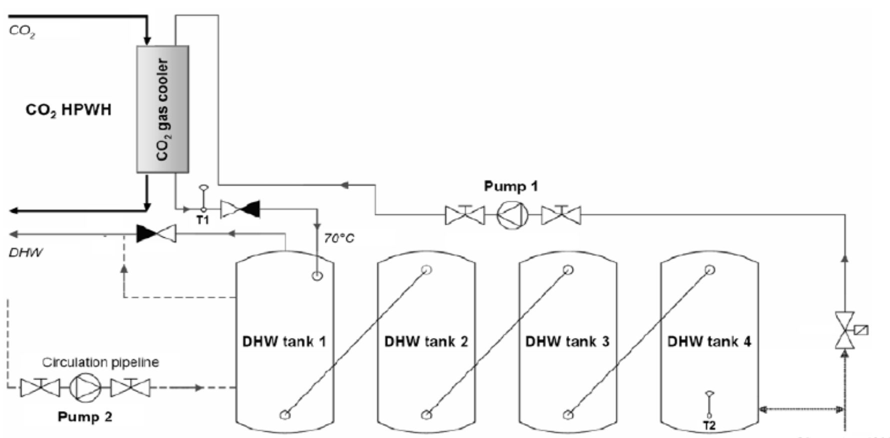


Figure 34: CO^2 heat pump for DWH system with multiple hot water tanks (Hjerkinn, 2007)

Chapter 4: Data Collection and Demand Profile

4.1 Data Collection – Longannet Power Station

This section shows the data and operating parameters of the Longannet cooling water outlet flume and the condensers. It is important that the correct temperatures are used in order to gain an understanding of how much energy is being lost and dissipated into the cooling canal. The data collection is an important part of the project and the data collected can be used for the modelling of the system. The data collected will be used for both the short term solution and the long term solution (outlined in the next section of the project). The data was collected from the Longannet power station cooling water report released in 1969, which includes a number of design factors for the pumps, outlet and canal system and the effects that the design has on the operation of the plant.

The circulating water system takes water from the estuary of the river Forth, which has a tide range between low and high water, with spring tides of around 17ft. The water system is deemed to be symphonic, fully for the tide cycle and partially for the low tide period when a seal pit maintains a higher level at the outfall. The system is made up of intake headworks with two sea water intake shafts and two tunnels transferring the sea water to the pumphouse. The intake headworks are fitted with screens to chlorinate the sea water. Then the water from the intake tunnels is screened before entering the main pumps, and then discharged to the culverts and thence to the condensers. There are four main C.W. pumps that each draw water through each individual screen and then to supply water to each of the two condensers for one unit (turbine and generator set). When the water passes through the condensers, it is then passed through the culverts to the recovery pit, then onto the cill to be carried to the outflow (cooling water flume). The water is then passed through a canal system to be rejected back into the river forth; where the cooling processes enables the water to renter the river at the same temperature it was drawn. The figure below shows an image of the cooling canal from the exit pumps to the exit flow into the river forth. The tables below show some of the data collected from the report regarding the circulating water system

Figure 35: Photo of Cooling Canal for Circulating Water (Google Maps, 2014)

C.W. System Flow				
Parameter	**Imperial Value**	**Imperial Unit**	**Metric Value**	**Metric Unit**
Turb Exh Pres (Abs)	0.9	"Hg	30.477	mbar
Heat rejected to CW	2440	10^6Btu's/Hr	2572614	MJ/hr
Circ Water Inlet Temp	52.5	^{o}F	11.4	^{o}C
CW Quantity for above conditions	248000	g.p.m.	18.79	m^3/s
Temp of condensate at Cond. Outlet	75.7	^{o}F	24.3	^{o}C
C.W. Temp Rise	48.74	^{o}F	9.3	^{o}C
No. Tubes per Cond	15,350			
Cond Surface	450,000	sq. Feet	41,806	m^2
Normal C.W. Flow to each cond.	140,000	g.p.m.	10.61	m^3/s
Velocity	5.30	ft./sec.	1.62	m/s
Friction head across water side at norm flow	11.41	ft.	341	mbar
Size of C.W. Inlet branch	48	"	1.22	m
Size of C.W. outlet branch	48	"	1.22	m
Tunnel dia	14	'	4.34	m
Tunnel Velocity	10.00	ft./sec.	3.05	m/s
Culverts (Octagonal)	12.25	'	3.73	m
Spring high-low tide range (Page 5)	17	'	5.18	m
Pump design flow at design tide level (-4.6' O.D.)	300,000	g.p.m.	22.73	m^3/s

Table 5: Circulating Water System Properties (G.H. Seymour, 1969)

Auxiliaries				
Parameter	**Imperial Value**	**Imperial Unit**	**Metric Value**	**Metric Unit**
MTLO's	3,000	g.p.m.	0.23	m^3/s
T.W. Recirc. Collers	5,000	g.p.m.	0.38	m^3/s
MBFPT Oil Coolers	250	g.p.m.	0.02	m^3/s
Exciter Oil Coolers	100	g.p.m.	0.01	m^3/s
Slip Ring Oil Coolers	60	g.p.m.	0.00	m^3/s
BFP Motor Coolers	1,400	g.p.m.	0.11	m^3/s
Boiler Fans & Mills	1,200	g.p.m.	0.09	m^3/s
Generator Tx Oil Coolers	1,650	g.p.m.	0.13	m^3/s
C.W. Screen Sprays	260	g.p.m.	0.02	m^3/s
Chlorination Plant	500	g.p.m.	0.04	m^3/s
CCR Air Conditioning	40	g.p.m.	0.00	m^3/s
Total Aux's	13,460	g.p.m.	1.02	m^3/s
Include 10% Wasteage	14,806	g.p.m.	1.12	m^3/s
Assume Half Ash Plant i/s	4,000	g.p.m.	0.30	m^3/s
Final Estimated Total	18,806	g.p.m.	1.42	m^3/s
Assume Total for Each Set	19,000	g.p.m.	1.44	m^3/s
Grand Total per set	299,000	g.p.m.	22.65	m^3/s
Pump Design Should Equal	300,000	g.p.m.	22.73	m^3/s
Total for Site at Full Load & 1 Ash Plant Phase	1,183,224	g.p.m.	89.65	m^3/s
Total (4 C.W. P/P's i/s)	1,200,000	g.p.m.	90.92	m^3/s
Diff.	16,776	g.p.m.	1.27	m^3/s

Table 6: Data from Auxiliary Systems (G.H. Seymour, 1969)

Summary				
At High Tide (C.W. P/P = 315,000 g.p.m.)	1,260,000	g.p.m.	95.47	m^3/s
Diff	76,776	g.p.m.	5.82	m^3/s
At Design Tide (C.W. P/P = 300,000 g.p.m.)	1,200,000	g.p.m.	90.92	m^3/s
Diff	16,776	g.p.m.	1.27	m^3/s
At Low Tide (C.W. P/P = 290,000 g.p.m.)	1,160,000	g.p.m.	87.89	m^3/s
Diff	-23,224	g.p.m.	-1.76	m^3/s

Table 7: Summary Table of Pump Flows (G.H. Seymour, 1969)

The tables above show three separate important sections of information regarding the cooling water system design. It should be mentioned that the most important table (table 5) shows some of the average temperatures of the water incoming and water being rejected to the canal system from the pumps. More importantly the table shows the significance of the heat and energy rejected to the circulating water through the condenser system. This data can be used to discover the various options open for recovering the heat fully or partially through some of the technologies shown in the sections above. As mentioned it will be important to specify a long term and short term solution to the Longannet power station, where the heat rejected to the circulating water through the condensers will be the source for heat and energy. The design parameters for the water pumps may also have a significant part to play in the solution to this project and therefore is shown in the other data tables. The diagram below describes the inlet and outlet conditions for a typical shell and tube heat exchanger used for each of the turbines generators on each of the power units (refer to first section to understand location of each condenser).

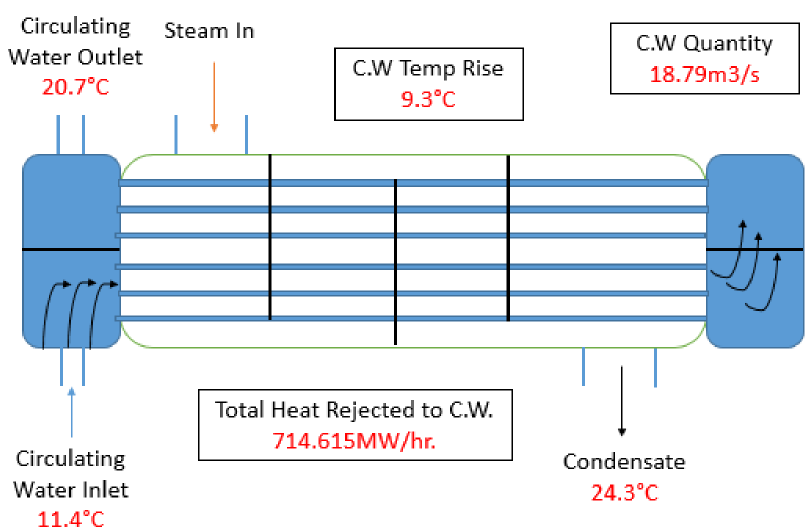


Figure 36: Condenser Conditions

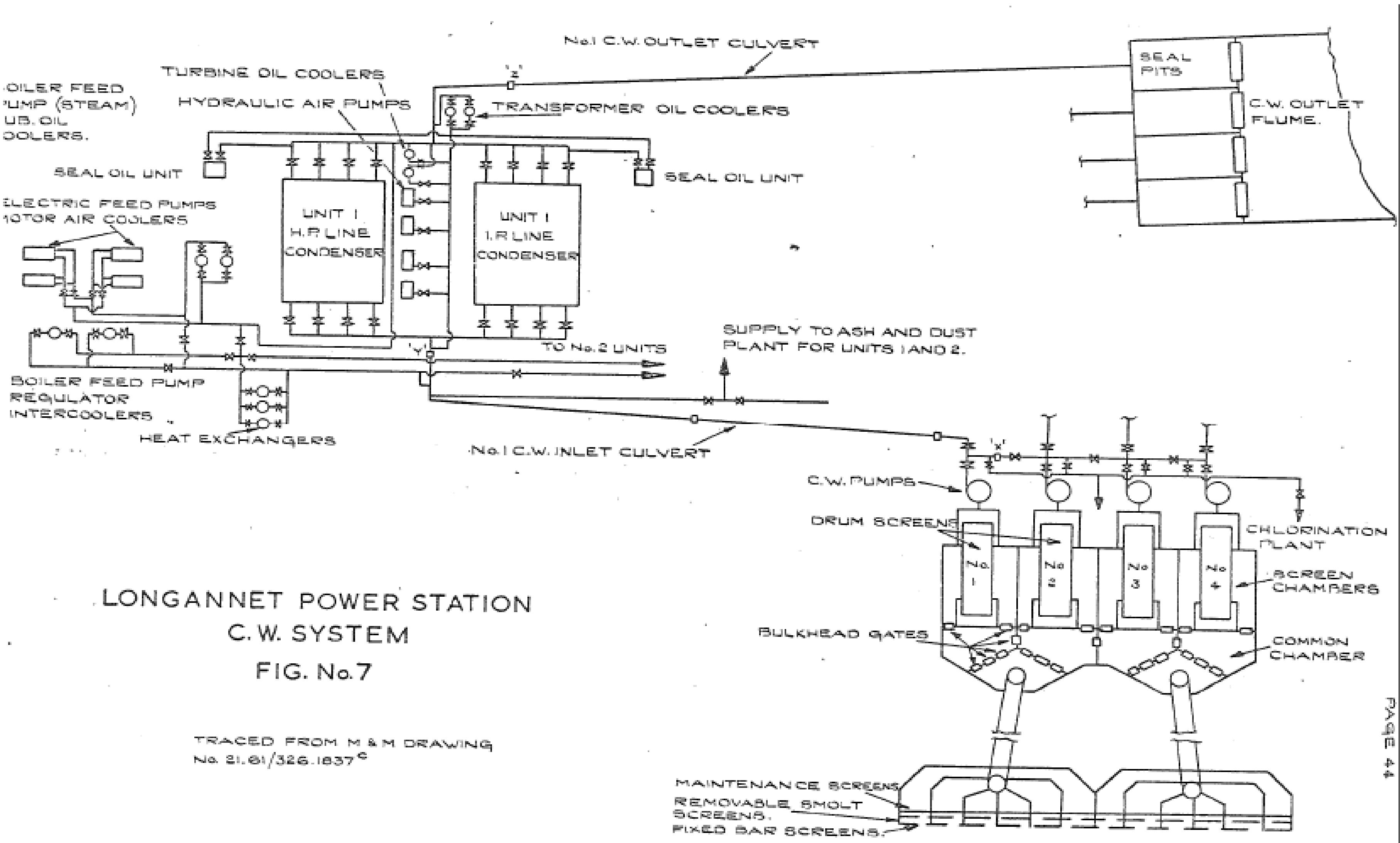


Figure 37: Longannet Power Station C.W System (G.H. Seymour, 1969)

4.4.1 Comparison of Longannet outlet vs. local temperatures

Understanding basic thermodynamic principles, the 2nd law describes the levels of performance of an energy system with regards to the quality of the energy provided. In this case, the amount of energy supplied in the circulating water is very high but the quality of heat is very poor, however by using appropriate technologies it may be possible to recovery and supply a good source of heat. In order to fully understand the system, and to rule out the need for using local sea and air temperatures for heat pump systems, the figures below shows the typical range of temperatures for the local area around Longannet. In any energy system there is a need for pumping water from the source to the system itself, for example in an open loop surface water heat pump system (shown in section above) water has to be pumped from the source to the evaporator in the heat pump system. As well as the power needed to work the compressor in the heat pump, there is also a serious demand and power needed to constantly drive the water pump. This has serious implications for the efficiency of the overall heat pump system and its suitability for certain water source applications. However in the case of Longannet, pumps are already provided at the seal pits before water is passed into the cooling canal and this may provide a suitable means to use an open source heat pump system for Longannet. This option favours the use of the circulating water as a suitable source for a heat pump system. Furthermore, the temperatures of the sea surrounding Longannet are much lower than the outlet temperatures of the circulating water. Figure 26 shows the average sea water temperatures in Aberdeen which is located in the same sea area in the north-east of Scotland. The average water temperatures for this area are given at 9.7°C, and fluctuate from 13°C in summer down to 6°C in winter months. This evidence proves that even though the quality of heat from Longannet is poor and temperatures are quite low, it has a greater potential than the source from the surrounding area for heat pumps, as the outflow temperatures will for the most part remain at the temperatures governed by the condensers, which are a fixed value.

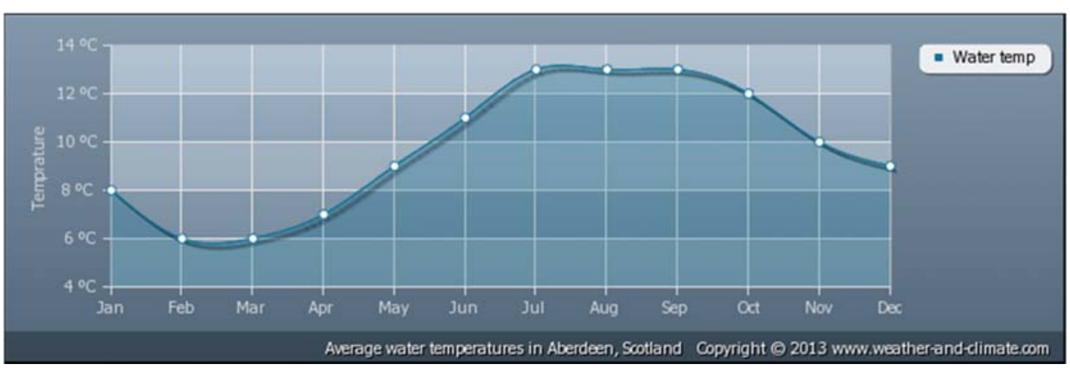


Figure 38: Average Sea Temperatures, Aberdeen, Scotland. (World Weather and Climate Information, 2013)

4.2 Demand Analysis

4.2.1 Application of a District Heating Network

The application of different technologies has been assessed in the previous sections, and it is easy to draw a conclusion that a heat pump system is a suitable application for the cooling water outlet flow at Longannet. The major issue concerning the project is that the vast amount of low quality and low temperature heat cannot be used on site, as the demand profile is too low and there is no direct use of heat in the power station. It is clear therefore to have a basic understanding of the local demand in the surrounding area, which could be further investigated by a subsequent project or by Scottish Power. Another major problem with the outflow of a heat pump system is that the flow rates of the circulating water and outflow of heat will at a much higher level than needed for the local area (this is discussed fully below). It was important therefore to look at the local area, local towns and industry and see if there is a potential for using some of the heat supplied by the heat pumps. District heating networks have come about by the drive to reduce fossil fuel consumption and increase the efficiency of buildings. In the case of low energy buildings, it may be possible in the future to remove some of the heating systems used currently, and replace these systems with renewable energy technology and also utilise excess heat from industry, commercial buildings and power stations. In order to recover this heat for example from a waste incineration plant, a form of district heating would be needed (Lund, 2009). An example of a district heating network that has proven its worth, is a study carried out for new housing developments in Norway that would eliminate the need for individual heating systems in residential housing. The results show that for a district heating system the CO^2 emissions would be lower than that of the original heating systems (Thyholt, 2007). The figure below outlines an example of some possible applications for the supply of heat from the district network.

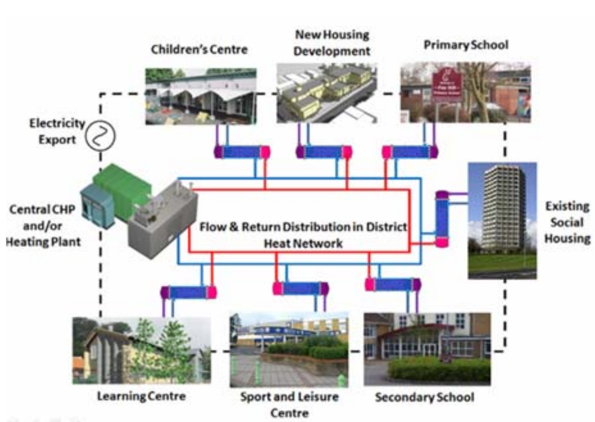


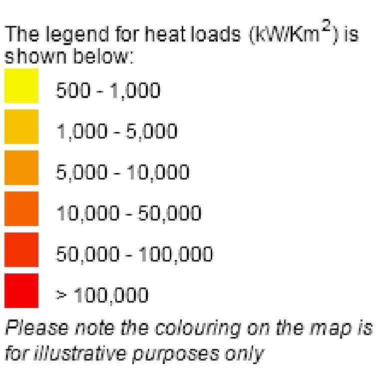
Figure 39: District Heating Network (Energy Saving Trust, 2013)

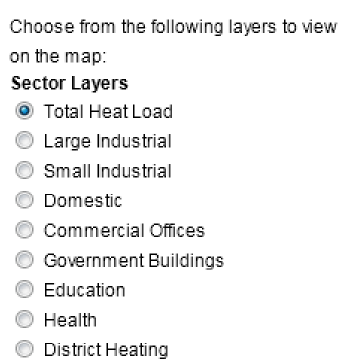
The district heating network has many advantages over traditional individual heating systems, some of which are listed below; (Combined Heat and Power Association , 2014)

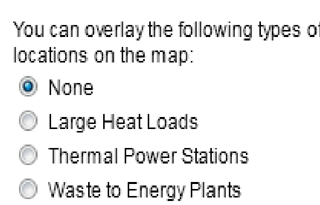
- Allows for efficient transportation of heat that can be used for variety of uses e.g. heating or hot water supply
- District heating enables the use of wide variety of renewable generation techniques that can be used to meet the area specific demand e.g. biomass, CHP, waste heat streams.
- Instead of many individual heating systems, the district heating allows for a more centralised control which is more manageable.
- Provides a means to reduce CO^2 emissions by optimising efficient energy supply control.
- Will allow for a more manageable supply and demand of heat and energy
- Will allow for an increase of renewable energy technologies that could be used to replace existing technologies e.g. oil and gas fired boilers.

4.2.2 Demand Profile of Local Area

There is a serious potential for the use of the hot water supply from the heat pump system to be utilised for the demand of some of the local areas around the Longannet power station. The Department of Energy and Climate Change published a national heat map which shows the average heating loads of certain towns across the UK, which can be used as brief reference for demand profiles. The CHP development map gives an indication of the total heat loads for specific areas, as well as an indication of some of the large heat loads in the UK, could prove as a useful tool for looking at local demand levels. The figures below show maps of various areas around Longannet power station. The tool also provides basic information about the different areas of choice. This includes details of the heating loads from domestic, government buildings and large industrial sites. The tool has a function to select areas and create a radius around the area in question. Details from these heat load maps will be critical in the application of a water source heat pump system and district heating network design. The blue circle in each map represents the location of Longannet.







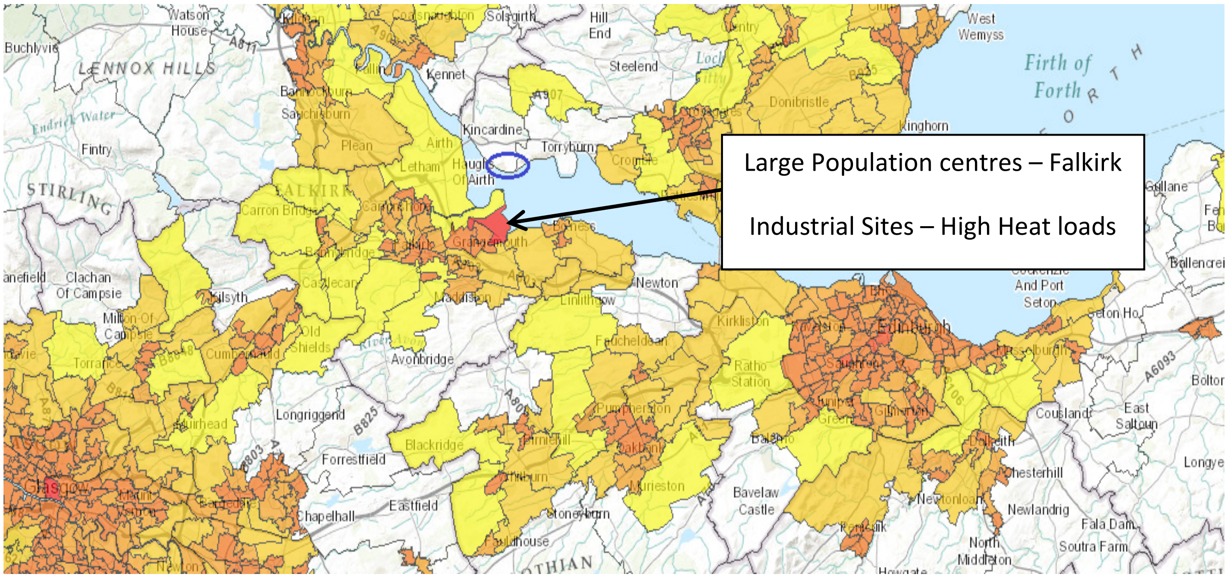


Figure 40: Map 1 - Area Heating loads (DECC, 2014)

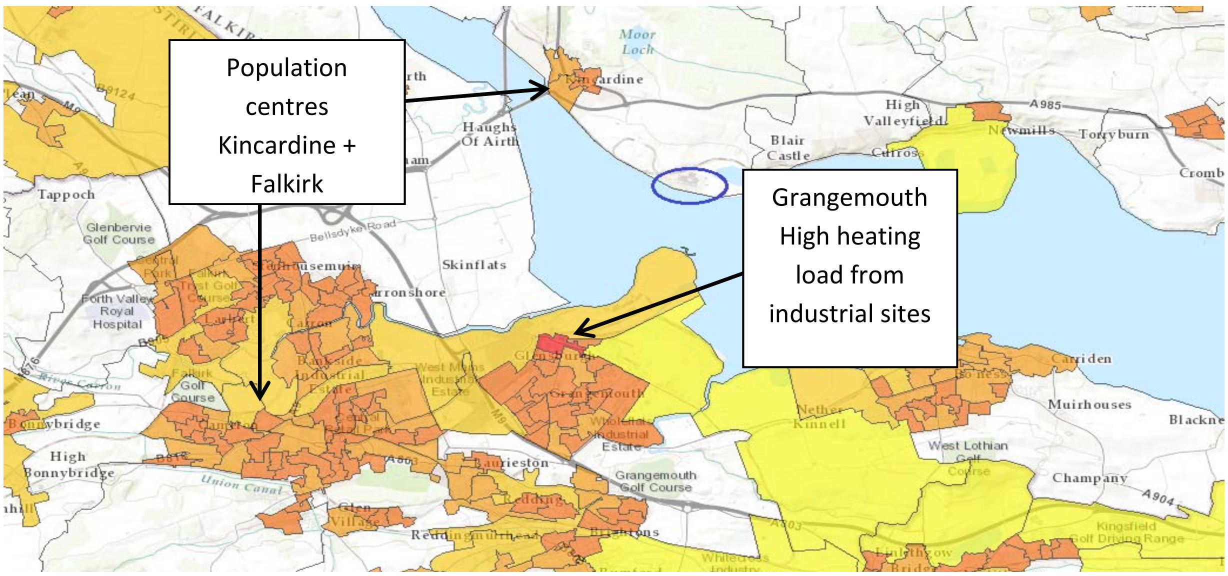


Figure 41: Map 2 - Area Heating loads (DECC, 2014)

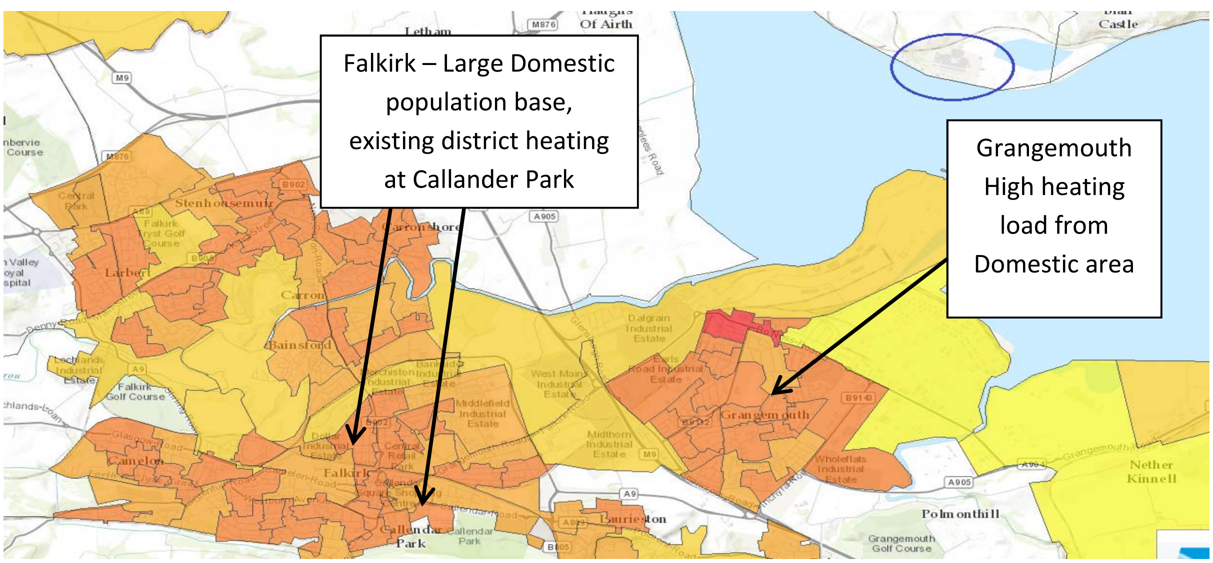


Figure 42: Map 3 - Area Heating Loads (DECC, 2014)

Grangemouth and Falkirk have a good domestic and non-domestic heat load profile, which a reasonable population base. It is clear that for some district heating schemes; the heat is passed to council or government buildings however the current scheme in Callander Park, uses a CHP system providing domestic hot water and heating services to the local estate. The opportunities across the firth of forth are endless, as the areas contain some high heating loads from large industrial sites as well as a large domestic area for housing. Kincardine also has a large potential for a district heating scheme, as it is located quite close to the power station, however the population base and the amount of heat energy required may be too low for the output of the heat pump systems. It should be mentioned that the heating load from the large industrial site area is measured at more than 100,000kW/m2, which is one of the highest ratings for the north of Scotland. The tables below show the heating demand per metre squared at these three possible locations. The figures also outline the location of some of the key sites that could be included in the study for district heating such as industrial sites and government owned buildings.

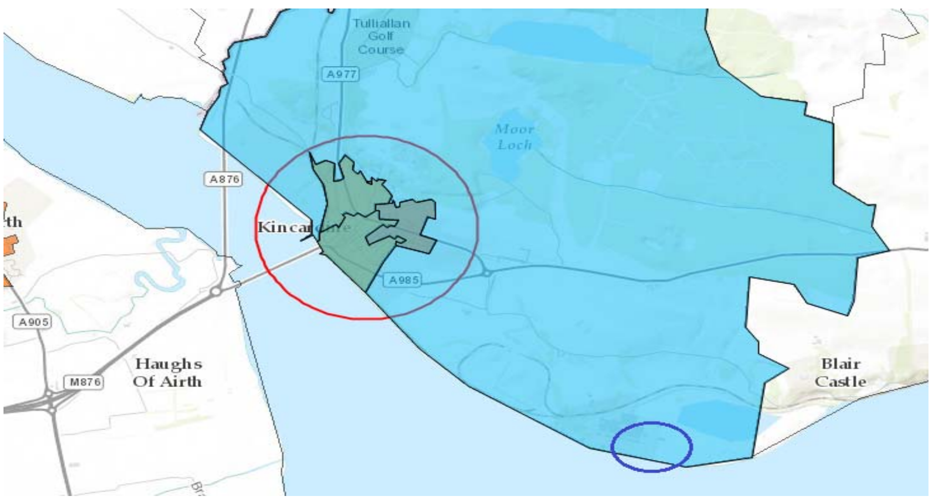


Figure 43: Map 4 Kincardine - Radius Area Heating Demand (DECC, 2014)

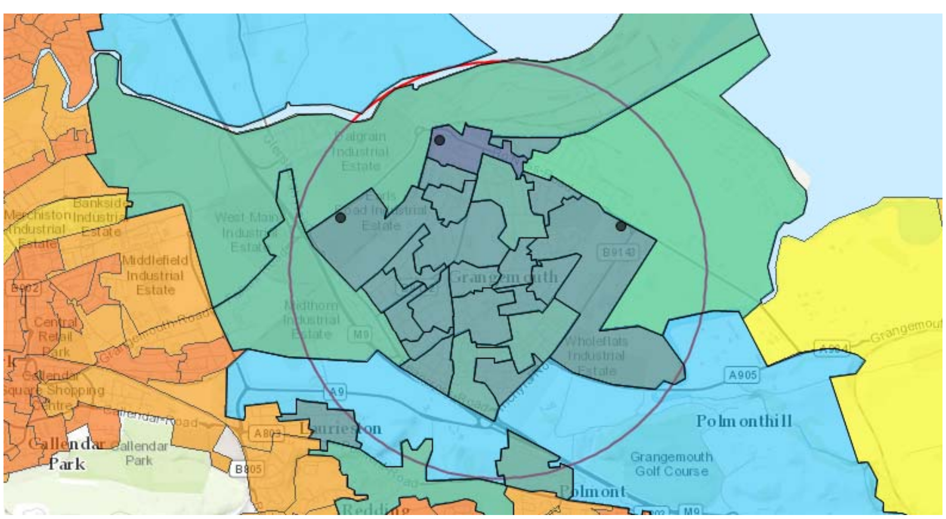


Figure 44: Map 5 Grangemouth - Radius Area Heating Demand (DECC, 2014)

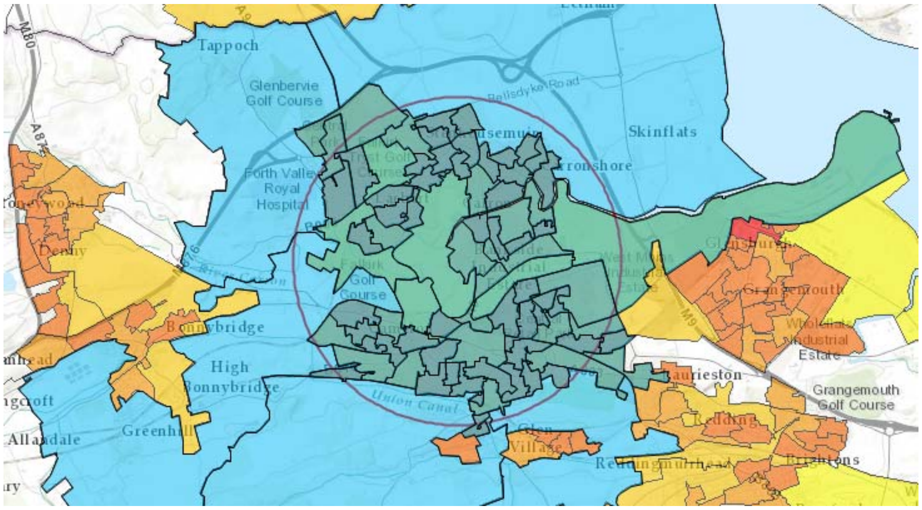


Figure 45: Map 6 Falkirk - Radius Area Heating Demand (DECC, 2014)

The sector total results below are from:	Kincardine	
	Share	**Total KW**
Communications and Transport	0%	0.195522
Commercial Offices	0.30%	28.63717
Domestic	94.93%	9021.5
Education	1.35%	127.9524
Government Buildings	0.58%	54.75991
Hotels	1.17%	111.2724
Health	0.08%	7.563255
Other	0.68%	64.15216
Small Industrial	0.15%	14.4774
Retail	0.28%	26.28617
Sport and Leisure	0.18%	16.84893
Warehouses	0.31%	29.23469
Total heat load in area	9502.879962	

Table 8: Total Heat Load – Kincardine (DECC, 2014)

The sector total results below are from	Grangemouth	
	Share	**Total KW**
Communications and Transport	0.03%	175.6937
Commercial Offices	0.12%	675.2394
Domestic	10.21%	56724.46
Education	0.05%	302.4931
Government Buildings	0.23%	1271.892
Hotels	0.25%	1411.589
Large Industrial	83.82%	465735.6
Health	0.01%	44.87471
Other	0.06%	347.1305
Small Industrial	4.45%	24722.9
Retail	0.31%	1746.736
Sport and Leisure	0.04%	228.9679
Warehouses	0.40%	2230.074
Total heat load in area	555617.6821	

Table 9: Total Heat Load - Grangemouth (DECC, 2014)

The sector total results below are from:	Falkirk	
	Share	**Total KW**
Communications and Transport	0.07%	159.0898
Commercial Offices	0.83%	1824.225
Domestic	83.58%	184168.2
Education	0.65%	1429.144
Government Buildings	1.85%	4087.142
Hotels	1.18%	2604.365
Health	1.22%	2678.812
Other	0.62%	1376.941
Small Industrial	5.84%	12871.41
Prisons	0.03%	72.8431
Retail	2.07%	4561.693
Sport and Leisure	0.39%	854.7196
Warehouses	1.66%	3652.215
Total heat load in area	220340.7608	

Table 10: Total Heat Load - Falkirk (DECC, 2014)

The figures and tables above show the 3 main areas of population around the power station that could be used potentially for a district heating scheme. In any case, this will be important to measure the losses in the pipe network and to analyse district heating in these specific areas. A basic analysis would show that the amount of energy available from the cooling water could be sufficient for some of the areas and locations shown above. The demand or total kW for these three areas is considerably high, with a large proportion of the heating demand in Grangemouth coming from large scale industrial. It should be noted however that a significant amount of the heat at the large industrial is supplied by a CHP unit. Information provided by the DECC development map shows the total heat demand for three large industrial sites located at Grangemouth, just east of the main town of Falkirk. The amount of heat demand however is quite small in comparison with the heat rejected to the circulating water. It may be possible to use a proportion of this heat or include a number of residential and domestic housing areas. It should be mentioned that the demand levels will fluctuate over time especially from the domestic sectors. The heating demand for example will change with respect to the size of house, type of energy system used, type of house, overall efficiency of the building and the number of occupants, as well as the occupancy rate over the course of one day i.e. heating demand will remain higher during peak times (morning and early evening) and the season/climatic factors that would affect the outdoor temperatures. The figures below show the general distance from the Longannet power station to these three key sites, which can be further analysed. There are many possibilities for a district heating scheme to include size, type and overall design of the pipeline network as well as the number, size and type of hot water storage tanks.

Figure 46: Map 7 - Distance to Kincardine (Google Maps, 2014)

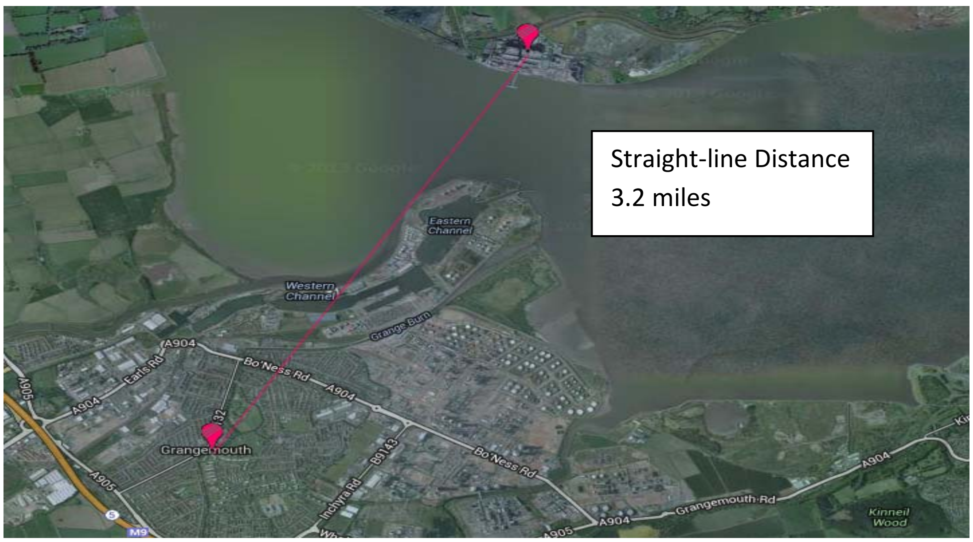


Figure 47: Map 8 - Distance to Grangemouth (Google Maps, 2014)

Figure 48: Map 9 - Distance to Falkirk (Google Maps, 2014)

4.3 Selection of Area and Further Analysis

As mentioned in the previous section the average demand profile for one of the towns will be necessary to look at the demand for hot water and for space heating. In order to fully evaluate the potential for using the CO^2 heat pump listed in the section above, a basic cost analysis will have to be worked out in order to look at the feasibility of introducing a district heating network with the supply from the heat pumps located at Longannet. The maps above show the average demand level for heating; however it will be important to look at the total demand profile for hot water in an average UK home, with average levels of occupancy and demand. The economic study will provide a cost per household for space heating and DHW using conventional boiler and fuel systems.

Once the demand profile has been established it will be necessary to then implement x number of heat pumps at Longannet to provide for the average conditions of the local town. For simplification of this study, the closest town (Kincardine) has been chosen which has the smallest population levels from the 3 sites. Over 90% of the demand from the town is from domestic housing and could be a viable place to implement central storage hot water tanks, to be used for DWH and space heating purposes. The map below shows a basic outline of the construction of the heat pump house, district network and central storage solution. Firstly, it will be important to work out the average cost for hot water in an average UK house, and then work out how much Longannet could sell its heat to the local town. This provides a feasibility analysis into the offsetting of costs for the homeowners, if they were to be supplied by the station heat pump house. The price for hot water however will depend on the initial costing of the heat pumps and the district network. The economics behind the project will also be ruled by the COP value of the heat pump systems. The COP value of each heat pump must be high enough to become economically viable for the rated heat output to match the demand of the local town.

Initial costs and output data will be drawn from the manufacturer's data, where service manuals provide an explicit number of performance graphs relating to the water source Eco-Cute system. This will provide a detailed account for the use of multiple water source heat pumps in a heat pump house. The COP value may vary due to the amount of condensing water leaving the station as each unit is switched on/off. One of the most important factors to also consider is the payback period for the installations as a result of the performance vs the price paid for each kW of heat supplied to the customer by the system.

Possible District Network design from heat pump house to the central storage tank located at site in Kincardine is shown in figures below. As house requirement for heat is for space heating and domestic hot water, there will be a return flow back into the secondary loop from the central storage tanks, so hot water in the first loop from the pump house would be fed into a heat exchanger, where water would be maintained at appropriate temperature for both purposes. In an open loop system, cold city water would be brought into the system at the central storage, and passed through the pump house loop to maintain levels of any water drawn off the tank for domestic hot water. Possible for a secondary heat exchange mechanism for space heating at each individual demand point, where cold water would be drawn in and passed through a heat exchanger to maintain temperatures for space heating.

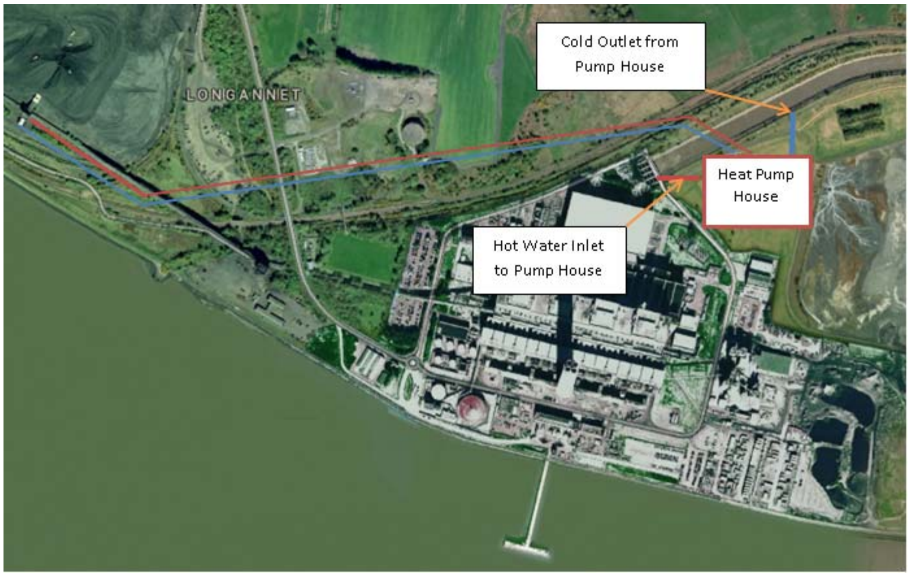


Figure 49: Photo 1 - District Heating Network

Figure 50: Photo 2 - District Heating Network

4.3.1 Detailed Demand Profile

In order to carry out a full demand analysis, it will be necessary to look at the local towns demand profile with respect to the total population and the average values for space heating and domestic hot water. It will then be important to work out the average cost of energy for these particular applications and how much an average household would pay for their energy bills. It is the hope that the price for energy provided by the heat pumps systems could provide a much lower cost than that of the conventional price for heating and hot water in a typical residential home. For simplification of the analysis, the biomass heating tool (carbon trust) incorporates a simple demand model for basic house types and will provide a daily and annual energy requirement per home, based on average persons per home and occupancy levels. The total average price paid by each home can then be calculated which will be the first stage in the economic study of heat pump systems. It will also be important to measure the demand profile for DHW and average hot water consumption. It should be noted that hot water demand and space heating demand will change with respect to a number of parameters, that are difficult to model dynamically such as; **boiler efficiency, fuel type, thermal store efficiency, pipe losses, heating mechanism type and efficiency, number of persons per home, daily occupancy levels, control temperatures required, building type** (including age, fabric, overall efficiency) and **overall demand variability with respect to living conditions and each homes personal heating requirement** (sustainable/non sustainable families.

As a requirement of the demand profile tool, it is necessary to input an average value for domestic hot water energy consumption per person per day. The energy saving trust provides average domestic hot water profile which was constructed as part of a study into a large number of dwellings. Results show typical hot water consumption and energy consumption in dwellings. The results showed an average household consumption of 122litres/day with a 95% confidence band, with average water delivery temperatures at 51.9°C. The mean energy content of the hot water was rated at 16.8MJ/day. The analysis and resulting data considered the impact of location, boiler type, number of occupants and the number of children per home. Heating period was also assessed as part of the study and the average heating time was found to be at 2.60hrs/day, with peak periods between 8.00am and 10.00am and again between 6.00pm and 11.00pm. The graph below shows the distribution of energy delivered to hot water in one sample dwelling. (Energy Saving Trust , 2008)

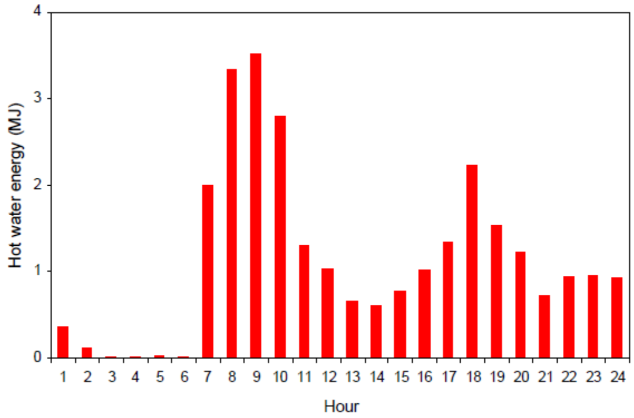


Figure 51: Distribution of energy delivered to hot water in one dwelling (Energy Saving Trust , 2008)

The graph below shows the distribution of hot water consumption in one sample dwelling form this study. This is also an important aspect to the design of any district hot water system, as the results from the whole study show the average consumption levels for domestic hot water. Furthermore, the hot water usage will impact greatly on the design and the requirement for supply water to be heated. In any case, city water will have to be drawn into the system, and heated through the heat pump house to replace the water drawn off the central storage tank, to meet the demand of the dwellings. Average temperature of the water to be heated in the dwellings varied with boiler type (standard or combination) and was found on to be around 52°C, much lower than the assumed 60°C average for domestic hot water.

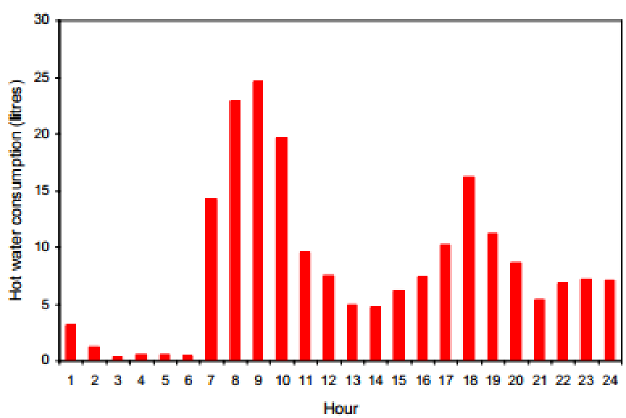


Figure 52: Average Hot water Consumption for one dwelling (Energy Saving Trust , 2008)

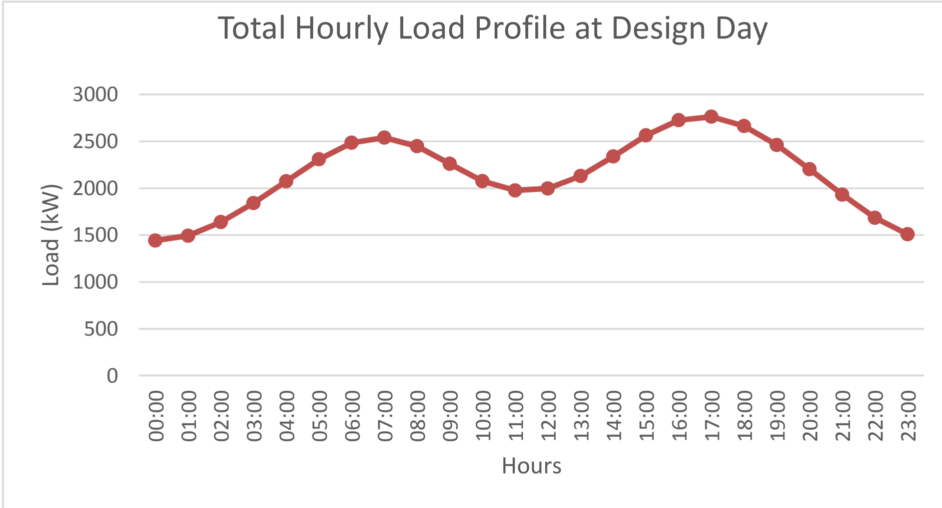
Kincardine has selected as an example for this analysis, and it is important to mention that the analysis for the other two sites will be the same. In order to achieve a basic set of results, the population of Kincardine has been divided by the average number of people per home (variations in demand from occupancy levels and frequency, amount of persons being children was disregarded for the study). The biomass demand tool, states a value for average heat demand at design day, energy demand at design day and the annual energy demand for various building types. The tool also incorporates the average daily hot water demand per day per person, which was estimated using the graphs and respected data above (1.16kW/hrs/day/per person). A housing estate was created on the tool with a range of modern to old homes. The total amount of properties in Kincardine was taken at 500, with 50 dwellings for each respected property type. The diagrams below show how each property was selected with the total number of this type with number of bedrooms per property specified. It is important to mention that this is a simple analysis of the demand profile and all parameters are neglected in this study. For example number of bedrooms varies dramatically, and correlates to both number of occupants and size of the house. The profiling and results are shown below. Outdoor design temperature was given at 0C and Glasgow was selected for the location.

Inputs

	Type	Age	Number of bedrooms	Number of houses of this type
House Type 1	Detached	2003-2007	4	50
House Type 2	Semi-detached	2003-2007	4	50
House Type 3	Detached bungalow	2003-2007	4	50
House Type 4	Detached	1983-2002	3	50
House Type 5	Semi-detached	1983-2002	3	50
House Type 6	Detached bungalow	1983-2002	3	50
House Type 7	Detached	Pre 1983	2	50
House Type 8	Detached bungalow	Pre 1983	2	50
House Type 9	Semi-detached	Pre 1983	2	50
House Type 10	Semi-detached bungalow	Pre 1983	1	50
			Total houses	500
Average Daily DHW:	1.16	kWh/person/day		

Total heating energy required			
Average heat demand at design day:		2,148	kW
Energy demand at design day:		51,558	kWh
Annual energy demand:	UPDATE	8,486,349	kWh

The demand data reads an annual energy demand of 8,486,349kWh with a peak heating load during an average design day of 2763kW. This value is an important factor in the selection of heat pumps at Longannet, where the output from the pump house will have to meet the capacity of this value to provide enough supply energy to meet the demand of the profile listed above. However, this can only be achieved when a full assessment of the heat pump system is taken into account including a cost assessment and COP performance over time.



As part of the assessment, a review of the price of energy for space heating and domestic hot water is very important to understand the feasibility of the district heating network and the heat pump systems. It is clear that one of the most important factors for this project is the price currently paid by the homeowners in the town for heating and hot water. The purpose of the heat pump network system is to lower the cost of energy bills for the residents, while reducing the emissions and current use of conventional sources of energy i.e. coal, oil and gas heating systems. Great Britain's housing energy fact file reported by the department of energy and climate change shows some basic but useful data that can be used for the project. As mentioned above, the varying parameters for demand analysis have been assumed and a simple profile has been constructed. In order to simplify the analysis, an average value for price per kWh has been taken from each fuel type available. The fuel type used for heating is not specified in the model above, and a simple number has been taken. A fully dynamic model would have to incorporate the fuel type and system type for each of the 500 homes shown above. For this assessment one type of each building will be selected with each fuel type with the respected number of occupants/bedrooms. The price per kWh for heating and hot water from the heat pump will depend on the COP value over time, where certain parameters such as outdoor temperatures may affect the work input to the pumps. Once a simple price comparison for each of the properties has been constructed, this pricing will be compared with the output pricing from the heat pumps. It should be mentioned that the price for energy from the heat pump is based on the input work to the compressor at any point when the system is running over the heat output from the unit. A full assessment into the cost of installations, district pipe network and central storage will also have to be considered. The network may also be eligible for a financial incentive from the government.

Chapter 5: Heat Pump Analysis for Heat Pump House

For this project, the Ecocute CO^2 heat pump has been selected as the heat pump of choice for the heat recovery heat pump house at Longannet power station. The reason for selecting this heat pump system is mainly due to the company's huge success at bringing CO^2 heat pumps onto the market all over the world. The company also claims to have running COP of up to 8 and being able to heat water up to 90°C effectively (perfect temperatures for heat distribution). The system can also be used for water cooling as well as heat recovery. Most studies carried out on Ecocute heat pumps have been gathered around air source heat pumps, however in this case an analysis into the suitability for the water source Eco-Cute will have to be carried out. It is also clear from the literature review that there no current conventional heat pumps that could provide heating of water of up to 90°C. Some of the past studies show that output temperatures would only be suitable for in situ low temperature heating systems. The Eco-Cute system is a good alternative for low grade heat recovery for high temperature distribution. The first initial concern is that the capacity of the heat pumps is far too small for the large amounts of heat and energy lost into the circulating water and that this vast amount of heat supply from the heat pump house will be too large for the demand of Kincardine. It is therefore clear that not all the heat will be recovered from the outlet flow at Longannet, however if the heat pumps can effectively provide enough energy to meet the demand profile of the local town at a lower cost of standard heating and hot water, then there is a serious potential for implementation. However having said this, costs of the distribution network will have to be weighed up against the performance of the pumps and its overall feasibility for the local town. Some of the specifications of the heat pump unit are given in the table below; which includes its range of use for PG cooling, water cooling and heat recovery.

Table 11: Ecocute Performance Details (Mayekawa, 2008)

Type		**PG Cooling**	**Water Cooling**	**Heat Recovery**
Model		HWW-2HTC		
Refrigerant		R-744 (CO^2)		
	Heating Ability (kW)	50	82	101.9
Performance	Cooling Ability (kW)	350	61.7	82.3
	Power Consumption (kW)	18.4	21.8	23.1
Power Supply		3 Phase AC200V 50Hz/60Hz		
Compressor	Model	Semi hermetic 2 Cylinder Reciprocating Compressor		
	Motor Designated Output	25 (kW)		
	Model	3 Cylinders		
Water Heater	Hot Water Condition (°F)	63/149		
	Water amount (L/min)	15	24	30

Items	Conditions			
Heat Exchanger	**Water Heater**	**Water Cooler**		
Type		Brine Cooling	Water Cooling	Heat Recovery
Liquid Type	Water	Brine	Water or Brine	Water or Brine
Inlet Temperature (°F)	11-88 11-143	-11-81	22-81.57	11-70
Outlet Temperature (°F)	143-198	-19.8-70.5	11-70.5	11-70.5
Inlet Water Pressure (Psi)	21-71			
Flow Rate (L/min)	8-35	>100		
Temp Diff Inlet-Outlet (°F)	>77	11		

Table 12: EcoCute Performance Details 2 (Mayekawa, 2008)

The tables above show some of the important features, specifications and the range of use for the water source Eco-Cute heat pump. From this initial data it is clear that the range of temperatures for heat recovery are suitable for water heating, however the inlet flow rate is far smaller than the outlet conditions to the cooling water canal. The maximum flow rate condition for each heat pump is measured at 35L/min. Even if a number of heat pumps are designed in series, the outlet flow conditions are unsuitable for the heat pumps. Considering this fact, only a small proportion of the heat contained in the circulating water will be extracted for use in the heat pump house. It is also clear that a closed loop system with subsequent flat plate heat exchangers may be the only viable solution to extracting heat from the water. The initial thought was to use the pumps on site to pump the water directly through to the heat pump house before being passed onto the cooling canal. It is evident that no heat exchange mechanism will support the high flow rates associated with the circulating water pumps and a closed loop system using either flat plates or coils may be the ideal selection for recovery of a proportion of the heat in the cooling canal. The tables below show some of the important data regarding the Eco-Cute heat pump from the operation manual. This data will provide a full understanding of the operation and parameters of the system for water heating at the two hot water supply temperatures. In order to fully understand the operating conditions a number of performance graphs will need to be generated showing the relation between return flow temperatures, heating capacity rates, power consumption and produced flow rate of water.

5.1 Service Manual Data Results

Heat source °C		Capacity kW	Inlet Water Temperature				
Inlet	Outlet		10°C	17°C	25°C	30°C	40°C
36	32	Heating	116	111	102	96	84
		Power	21.6	22.2	24.2	24.5	26
22	17	Heating	106	101	93	87	74
		Power	22.5	23.1	24	24.3	25.6
12	7	Heating	86	82	76	72	62
		Power	21.2	21.8	23.2	23.8	24.4
-5	-9	Heating	52	50	46	43	39
		Power	17.3	18.4	18.2	18.8	19.7

Table 13: Heating Capacity vs. Return Inlet Temperature (65°C)

Heat source °C		Capacity kW	Inlet Water Temperature				
Inlet	Outlet		10°C	17°C	25°C	45°C	65°C
36	32	Heating	108	101	93	71	40
		Power	27.3	26.7	26.9	27.1	27.2
22	17	Heating	105	92	85	64	39
		Power	27	26.4	26.6	27	27.1
12	7	Heating	83	76	71	56	35
		Power	24.8	24.9	24.9	25.3	25.7
-5	-9	Heating	50	48	38	28	21
		Power	19.4	19.6	19	16.6	20.2

Table 14: Heating Capacity vs. Return Inlet Temperature (90°C)

Under these performance tables, a number of performance graphs can be created using data provided by the user servicing manual. The two tables above show the conditions for both supply water temperatures, 65°C and 90°C. The tables initially show a good potential for hot water recovery and heating to these suitable temperatures. The heating capacity and the power required at the compressor are judged by the return inlet conditions of the water to the heat pump system, under an inlet heat source condition. The flow rate conditions of the water into the heat pump will also be a significant factor in heat pumps as there is a restriction flow rate for the heat pump system. The graphs below show the results for heating capacity against the return inlet water temperature for the four source heat temperature bands at both 65°C and 90°C and the hot water flow from the heat pump vs the return inlet temperature for each source condition at 65°C and 90°C. Subsequent graphs include power consumption vs the return source inlet temperature for the same conditions given above. From these graphs and data given above, a graph of the COP values vs source inlet temperature is generated to enable an understanding of the various operating conditions and parameters for the heat pump system. The COP value for the selected conditions will be an important factor in the overall cost of running and selling hot water from the system.

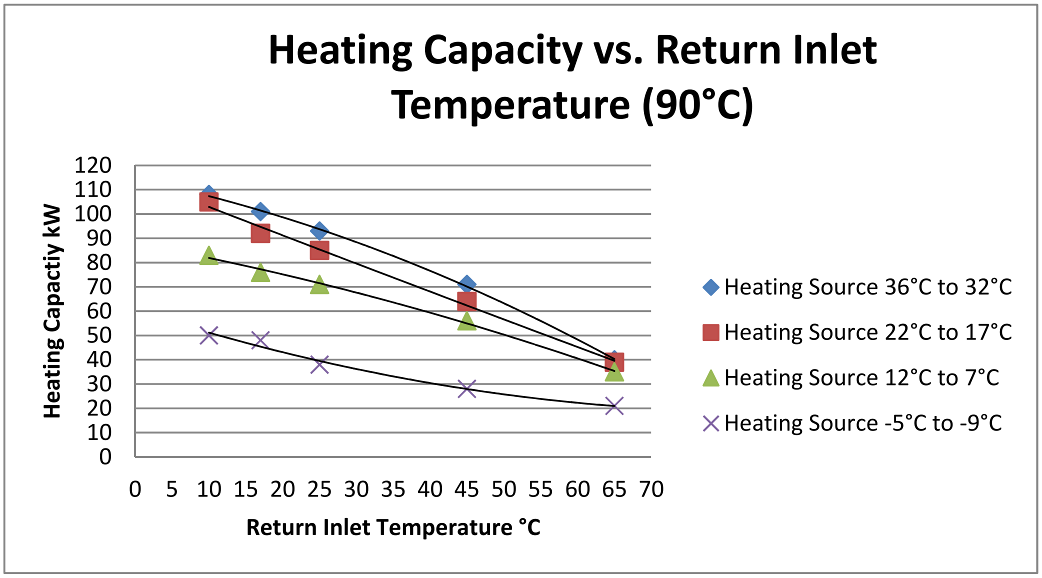


Figure 54: Heating Capacity vs. Return Inlet Temperature (90°C)

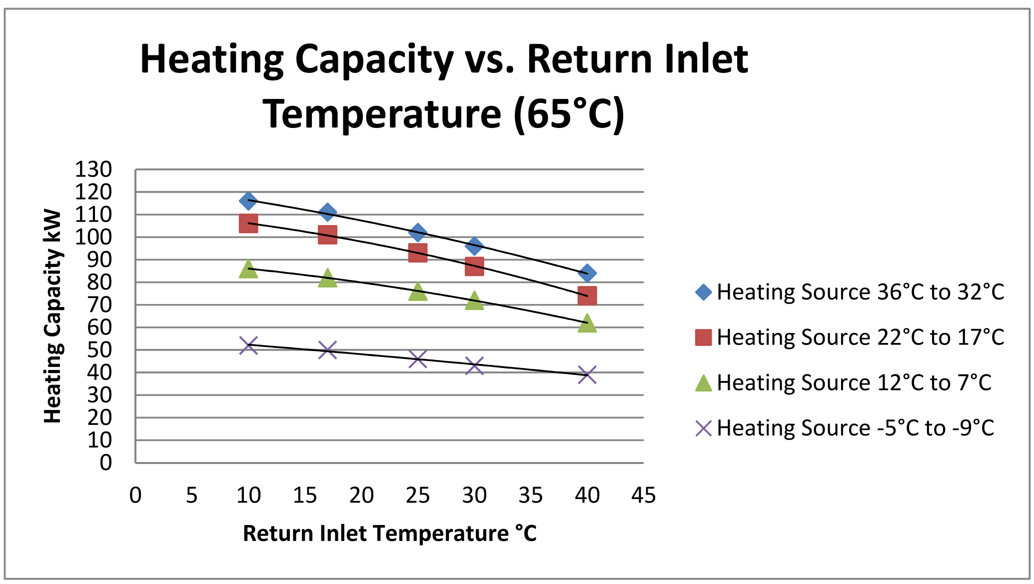


Figure 53: Heating Capacity vs. Return Inlet Temperature (65°C)

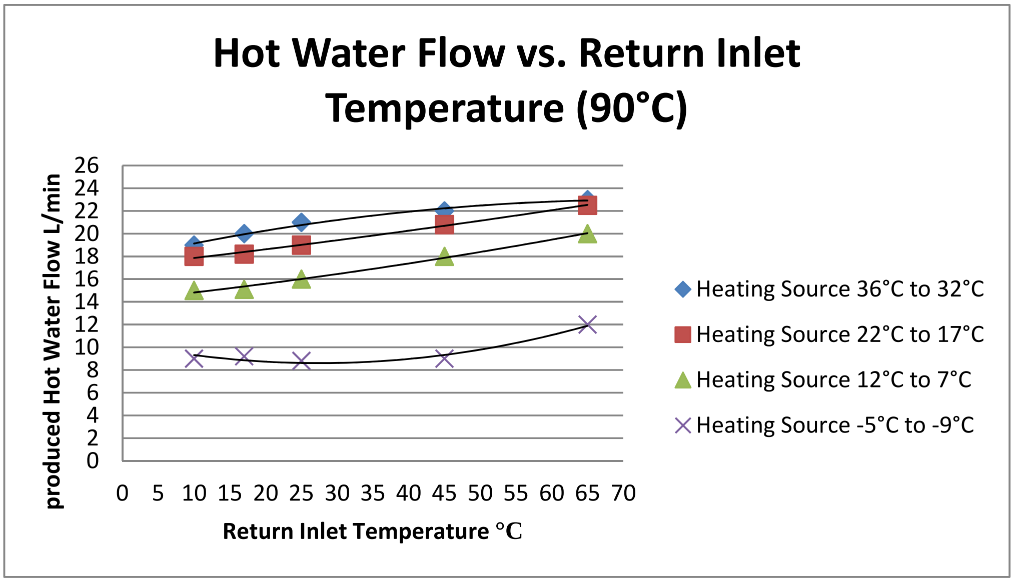


Figure 55: Hot Water Flow vs. Return Inlet Temperature (90°C)

The graphs below show the impact of the various return water inlet temperatures on the flow rate from the heat pump for both a constant outlet temperature of 65°C and 90°C. The graphs also show the flow rate change across each of the four inlet temperatures from the heating source (water). The corresponding tables for the graphs shown below are given in Appendix A, and show each measured flow rate under each parameter condition.

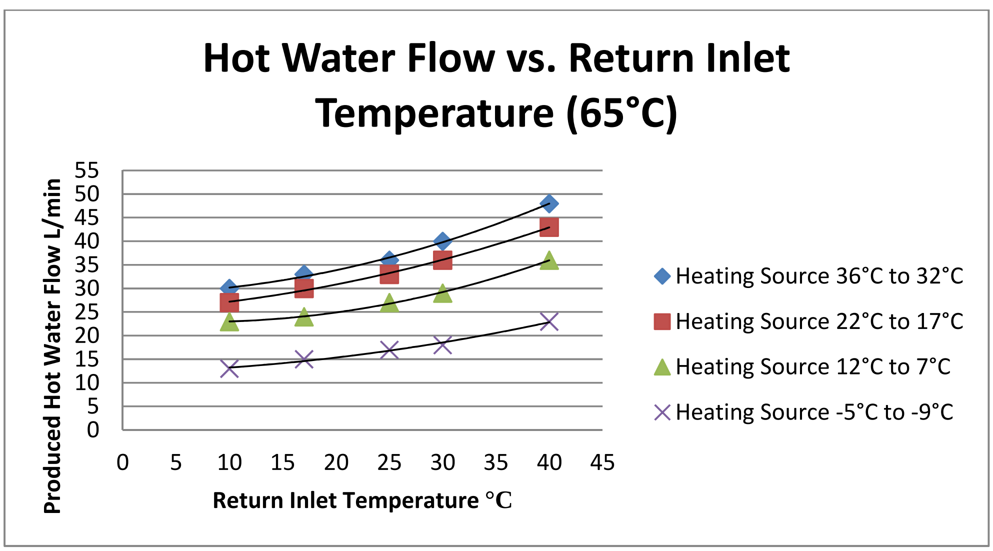


Figure 56: Hot Water Flow vs. Return Inlet Temperature (65°C)

An important measure in the project is the overall COP of the heat pump as it works under various operating conditions. We can extract the COP value from the total power consumption of the unit over the heating capacity it provides. The graphs below show the power consumption of the Ecocute system under each of the four inlet temperatures to the evaporator, with the data points showing the consumption at each constant return flow temperature back into the gas cooler. One graph displays the results for a constant hot water fed at a temperature of 65°C and the other displays results for 90°C. It should be noted that for this study the 90°C data will be more important for a district heating proposal, as with an open or closed loop system at the supply side and a considerable distance for the hot water to travel, it can be assumed that 65°C will not provide the necessary temperature for hot water and space heating. The power consumption tables can also be viewed in Appendix A.

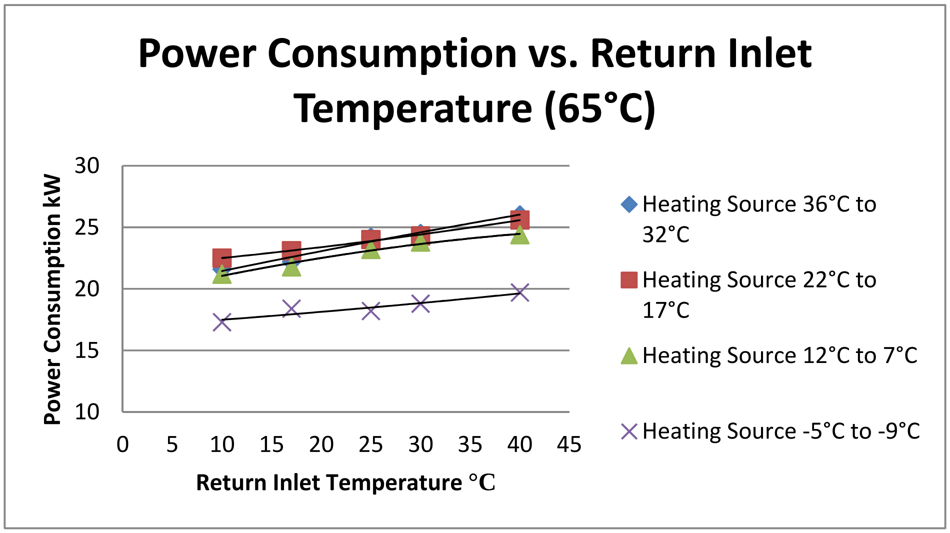


Figure 57: Power Consumption vs. Return Inlet Temperature (65°C)

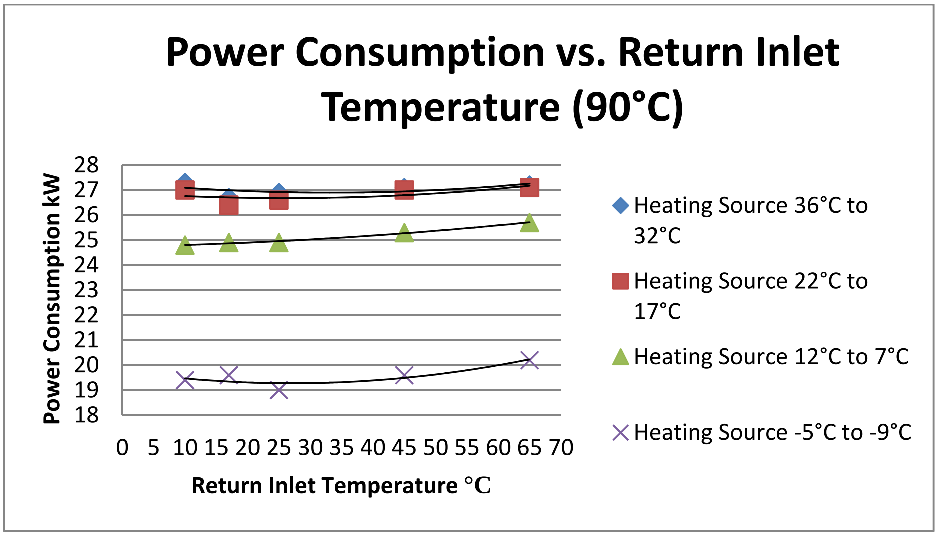


Figure 58: Power Consumption vs. Return Inlet Temperature (90°C)

For the 90°C graph, it is clear that the change in power consumption from inlet conditions 36°C to 22°C is minimal in comparison with the lower inlet condition temperatures. The graphs also show that the change in return inlet temperature into the gas cooler also has minimal effect on the power consumption of the unit. More importantly the tables and graphs below shows the COP measured results for the same conditions stated above. The manufacture states that the unit can run up to a COP of 8, however these are likely to be optimum conditions and far from the conditions given at the cooling outlet of Longannet. Also the inlet temperatures to the evaporator are also unrealistic for the temperatures of the circulating water and a further analysis will be needed. The graphs show a considerable drop in COP value as the return inlet temperature increases. The results also show that the change in heat source temperature also has a considerable impact on the operating COP. It should be noted that these results are steady state values and are not realistic for true operation of the heat pump cycle. It should also be noted that there is a considerable difference in the COP values between the outlet water temperature of 65°C and 90°C, where the COP drops to as low as 1.4 where the return water inlet temperature to the gas cooler is 65°C and the source temperature is between 36°C ad 22°C. It is very clear that the return water back into the gas cooler has a significant impact on the COP and the running of the unit. Therefore as the temperature increases, the cost of running the heat pump will increase dramatically. In domestic hot water systems only, the return line temperature could be maintained at a low temperature (as the return line is a constant feed from the mains water supply) of around 10°C. However in the case of space heating and domestic hot water, in a single heat pump system the return water from the heating systems will reduce the COP of the heat pump as the water fed back to the gas cooler for another loop cycle will contain a considerable water temperature.

Heat source °C			**Inlet Water Temperature**				
Inlet	**Outlet**		**10°C**	**17°C**	**25°C**	**30°C**	**40°C**
36	**32**	COP	5.387189	5	4.221281	3.918367	3.230769
22	**17**	COP	4.711111	4.372294	3.875	3.580247	2.890625
12	**7**	COP	4.056604	3.761468	3.275862	3.02521	2.540984
-5	**-9**	COP	3.00578	2.717391	2.527473	2.287234	1.979695

Table 15: COP vs Return Inlet Water Temperature (65°C)

Heat source °C			Inlet Water Temperature				
Inlet	**Outlet**		**10°C**	**17°C**	**25°C**	**45°C**	**65°C**
36	**32**	COP	3.956044	3.782772	3.457249	2.619926	1.470588
22	**17**	COP	3.888889	3.484848	3.195489	2.37037	1.439114
12	**7**	COP	3.346774	3.052209	2.851406	2.213439	1.361868
-5	**-9**	COP	2.57732	2.44898	2	1.686747	1.039604

Table 16: COP vs Return Inlet Water Temperature (90°C)

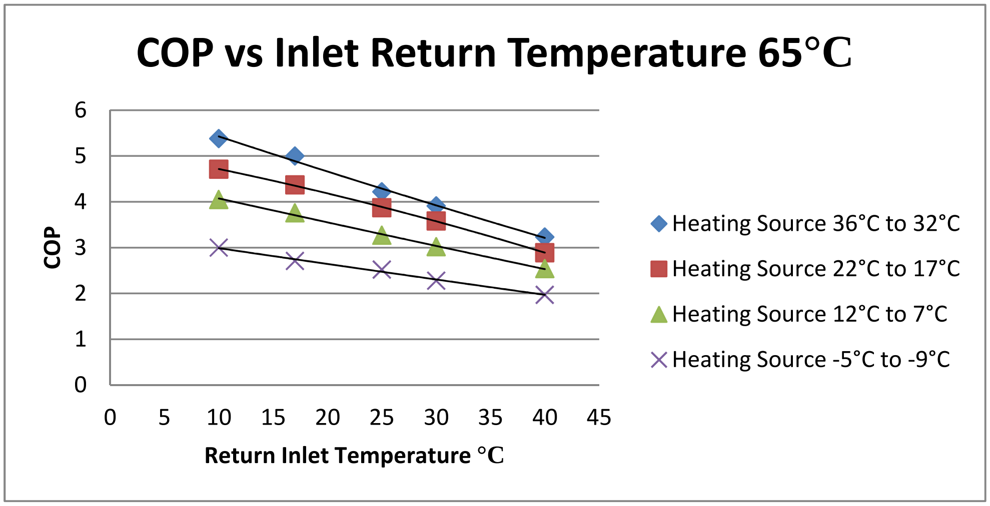


Figure 59: COP vs Return Inlet Water Temperature (65°C)

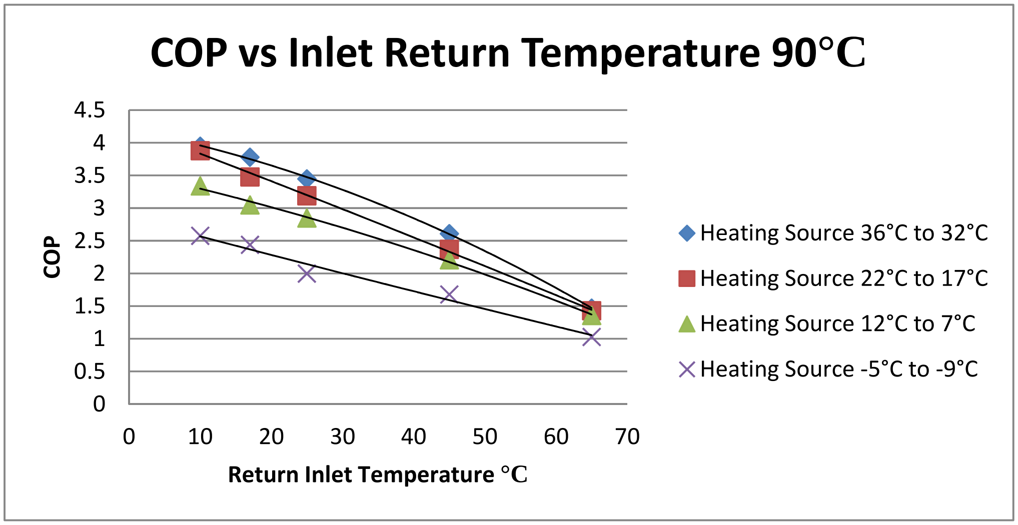


Figure 60: COP vs Return Inlet Water Temperature (90°C)

5.1 Basic Assessment of Operational Cost

The graphs above show that the water source heat pump could be a viable solution to heat recovery at Longannet power station. Under the servicing manual and results correlated from the manufacturer it is clear that the Eco-Cute heat pump could provide heating at a reasonable COP value, under the various conditions outlined above. However, economically the heat pumps may not be viable, and the COP value will affect the overall running cost of the pumps and the running cost and payback on the capital cost of the heat pumps and distribution network will have to be considered before a conclusion can be drawn and presented. Firstly, based on the demand data provided by the energy saving trust tool and the data provided by the service manual, the output from the heat pumps must be designed to meet the current demand conditions of the local town. For this particular project, a number of heat pumps will be needed as the capacity of the pump for heating is around 100kW. At this stage of the project the inlet conditions to the heat pump house (water source) will be given as the outlet temperature of the condensers and to the pumps (as shown in Longannet circulating water diagram), as the heating source is specified between 22°C inlet and 17°C return outlet. In order to evaluate the cost benefit of the heat pump, a study into one single pump will be carried out under variable COP conditions, outlined by the various parameters given above. The cost of the heat pump will be based on the price per Kwh per day of full running conditions. The cost of running the heat pump will be the price paid per Kwh of electricity to provide power to the compressor. The cost of running the heat pump will have to be compared with the cost of heating using conventional fuels, which will determine if the heat pumps are economically viable. Under all conditions stated in the graphs above, cost of running the heat pump for 24 hours under each specific COP is given in the table and graph below. The cost of running the heat pump has been specified while running at full capacity over 24 hours. The cost of one unit of electricity (pence/kWh) is specified as an average value at 13.52p/kWh (Energy Saving Trust, 2014). The table shows total cost for each 24 hour period, with the COP value under each condition (inlet source temperature and return temperature) and the respected power consumption of the compressor at each COP value. Once the value for cost at each parameter is calculated, it will then be necessary to outline the cost for the source temperatures at Longannet and the return inlet temperature. The total amount of heat pumps needed under these conditions will be specified, along with the total cost of running the heat pump per day. This overall cost will be weighed against the average cost per household for space heating and hot water.

Heat source °C Inlet	Heat source °C Outlet	65°C 24 Hours	Inlet Water Temperature 10°C	17°C	25°C	30°C	40°C
36	32	COP	5.387189	5	4.221281	3.918367	3.230769
		Energy Consumption (kWh)	518.4	532.8	580.8	588	624
		Cost (£/24hrs)	70.08768	72.03456	78.52416	79.4976	84.3648
22	17	COP	4.711111	4.372294	3.875	3.580247	2.890625
		Energy Consumption (kWh)	540	554.4	576	583.2	614.4
		Cost (£/24hrs)	73.008	74.95488	77.8752	78.84864	83.06688
12	7	COP	4.056604	3.761468	3.275862	3.02521	2.540984
		Energy Consumption (kWh)	508.8	523.2	556.8	571.2	585.6
		Cost (£/24hrs)	68.78976	70.73664	75.27936	77.22624	79.17312
-5	-9	COP	3.00578	2.717391	2.527473	2.287234	1.979695
		Energy Consumption (kWh)	415.2	441.6	436.8	451.2	472.8
		Cost (£/24hrs)	56.13504	59.70432	59.05536	61.00224	63.92256

Table 17: Cost vs. COP Analysis (65°C)

Heat source °C Inlet	Heat source °C Outlet	90°C 24 Hours	Inlet Water Temperature 10°C	17°C	25°C	45°C	65°C
36	32	COP	3.956044	3.782772	3.457249	2.619926	1.470588
		Energy Consumption (kWh)	655.2	640.8	645.6	650.4	652.8
		Cost (£/24hrs)	88.58304	86.63616	87.28512	87.93408	88.25856
22	17	COP	3.888889	3.484848	3.195489	2.37037	1.439114
		Energy Consumption (kWh)	648	633.6	638.4	648	650.4
		Cost (£/24hrs)	87.6096	85.66272	86.31168	87.6096	87.93408
12	7	COP	3.346774	3.052209	2.851406	2.213439	1.361868
		Energy Consumption (kWh)	595.2	597.6	597.6	607.2	616.8
		Cost (£/24hrs)	80.47104	80.79552	80.79552	82.09344	83.39136
-5	-9	COP	2.57732	2.44898	2	1.686747	1.039604
		Energy Consumption (kWh)	465.6	470.4	456	398.4	484.8
		Cost (£/24hrs)	62.94912	63.59808	61.6512	53.86368	65.54496

Table 18: Cost vs. COP Analysis (90°C)

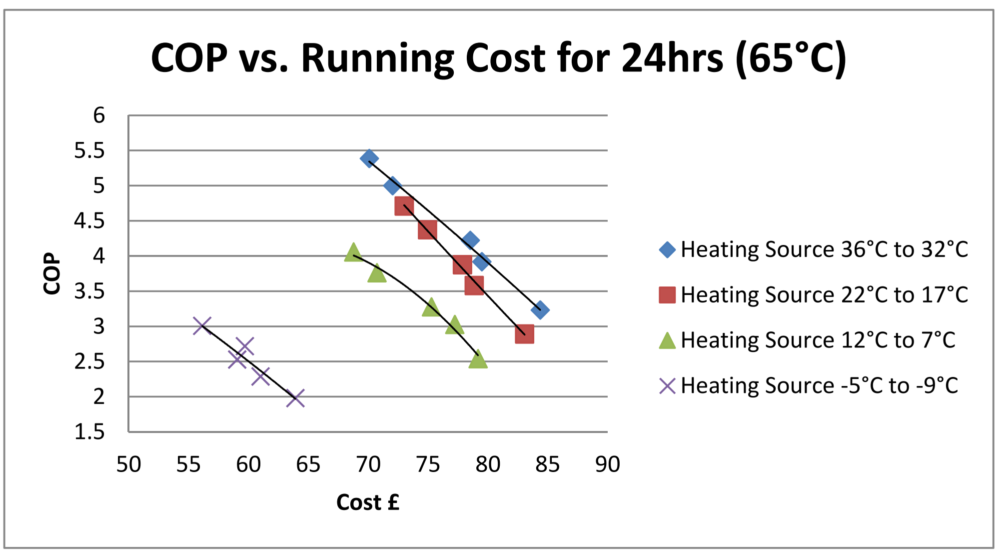


Figure 61: COP vs. Running Cost for 24hrs (65°C)

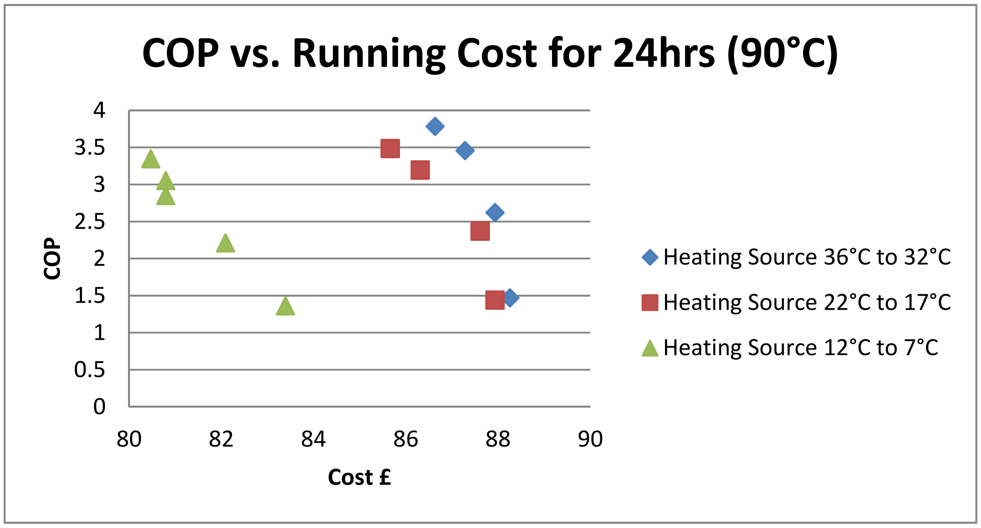


Figure 62: COP vs. Running Cost for 24hrs (90°C)

The data above shows that as the COP decreases the cost of energy from the heat pump increases (due to the ratio of input power vs useful energy out reduces) for both output water temperatures. There is a liner positive correlation between power consumption and cost per day. Both graphs show a significant difference between each heating source temperature and the return inlet temperature. As the inlet return temperature increases the COP value decreases quite significantly and the cost associated with running the heat pump increases. The cost difference at each return temperature at outlet water temperature 65°C is much higher than of 90°C outlet. The COP value for each parameter is also worked out from the heat pump working at full heating capacity, which would be an unreasonable case for real time operation. For the heat pump system to be a viable heat recovery system, the cost of running a series of heat pumps to match the demand of the local town must be lower than the price paid for other heating fuels in the home. As specified above the heat pumps will provide hot water for distribution across a series of pipeline networks that can be fed into a central storage tank, where heat will be transferred to each domestic property.

5.2 Economic Considerations for Longannet Operation

It is clear from the data above that the impact on water source temperature and return water temperature into the heat pump has a significant impact on the COP of the heat pump. It is also clear that the ideal situation for the extraction of water from the circuiting water would be an open loop scheme where a pump could provide sufficient water to the heat pump house. This would require a separate pump that could extract water at the heat recovery input condition of 30L/min for the conditions shown above. The open loop scheme would also cut costs quite considerably at the power station side. Firstly, it is important to measure the exact conditions of power consumption, heating capacity, COP value, produced water flow rate and return water temperatures at various circulating water source temperatures. The data above shows the range of values from 22-12°C for source temperatures. By interpolating the data given at these various parameters, it was necessary to show values ranging from 15-21°C. The cooling water outlet is specified to 20.7°C from the data shown above from Longannet circulating water data. The tables and graphs below show the COP values and cost of running the heat pump over a 24hr period using the variable source temperatures 16-21°C at each return water inlet temperature.

Inlet Source Temp °C		Return Water Inlet Temperature °C				
		10	17	25	45	65
16	COP	3.574766	3.231373	2.994527	2.278676	1.393755
	Energy Consumption (kWh)	616.32	612	613.92	623.52	630.24
	Cost (£/24hrs)	83.32646	82.7424	83.00198	84.2999	85.20845
17	COP	3.629344	3.274854	3.029126	2.294455	1.401515
	Energy Consumption (kWh)	621.6	615.6	618	627.6	633.6
	Cost (£/24hrs)	84.04032	83.22912	83.5536	84.85152	85.66272
18	COP	3.683002	3.317829	3.063272	2.31003	1.409194
	Energy Consumption (kWh)	626.88	619.2	622.08	631.68	636.96
	Cost (£/24hrs)	84.75418	83.71584	84.10522	85.40314	86.11699
19	COP	3.735763	3.360308	3.096972	2.325406	1.416792
	Energy Consumption (kWh)	632.16	622.8	626.16	635.76	640.32
	Cost (£/24hrs)	85.46803	84.20256	84.65683	85.95475	86.57126
20	COP	3.787651	3.402299	3.130236	2.340585	1.42431
	Energy Consumption (kWh)	637.44	626.4	630.24	639.84	643.68
	Cost (£/24hrs)	86.18189	84.68928	85.20845	86.50637	87.02554
21	COP	3.838686	3.44381	3.163072	2.355572	1.431751
	Energy Consumption (kWh)	642.72	630	634.32	643.92	647.04
	Cost (£/24hrs)	86.89574	85.176	85.76006	87.05798	87.47981

Table 19: Additional COP Cost Analysis (90°C)

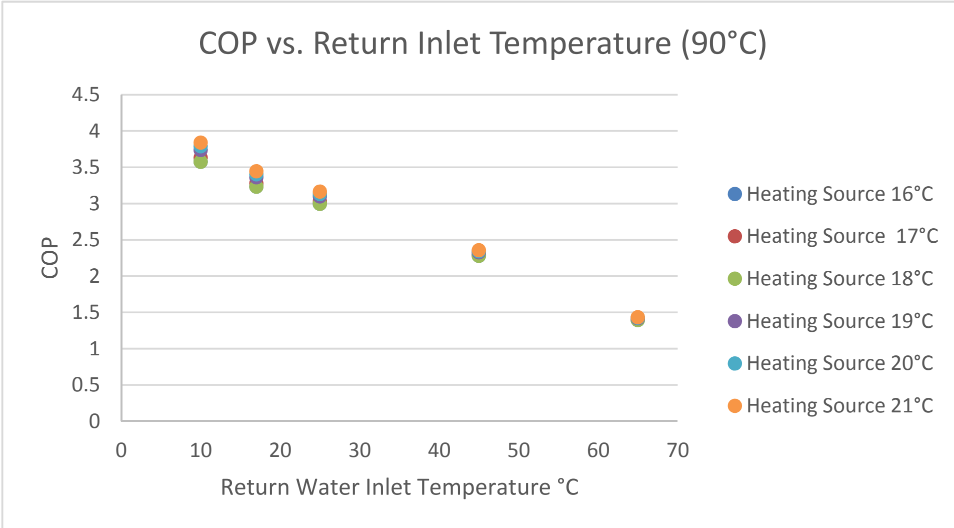


Figure 63: COP vs. Return Inlet Temperature (90°C)

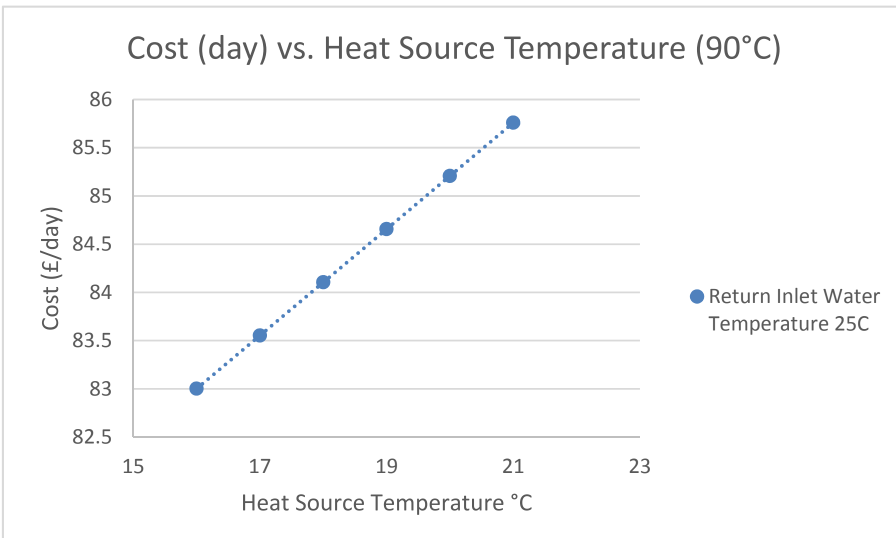


Figure 64: Cost per Day vs. Heat Source Temperature (90°C)

The results show that the difference in COP and running cost over the various source temperatures are quite small. However it should be noted that the return temperature has a significant impact on the overall COP of the system and the total running cost. It is important therefore to measures the return water inlet temperature from the central storage tanks. It is also apparent that the relationship between the running costs per day of the heat pump against various inlet source temperatures to the evaporator is linear (as the source temperature increases the cost per day also increases). However, having said that this the capacity of each heat pump increases as the source temperature increases and therefore the COP is higher. In order to fully access the different source temperatures it is also important to look at the produced hot water flow from heat pump. The table and graph below shows the produced hot water flow rates for 90°C. The produced flow rate of hot water is an important aspect to the design of the heat pumps to provide enough hot water to supply the hot water and space heating demand.

Heat source °C		Inlet Water Temperature				
		10°C	**17°C**	**25°C**	**45°C**	**65°C**
16	Flow rate L/min	16.2	16.34	17.2	19.12	21.81818
17	Flow rate L/min	16.5	16.65	17.5	19.4	21.93182
18	Flow rate L/min	16.8	16.96	17.8	19.68	22.04545
19	Flow rate L/min	17.1	17.27	18.1	19.96	22.15909
20	Flow rate L/min	17.4	17.58	18.4	20.24	22.27273
21	Flow rate L/min	17.7	17.89	18.7	20.52	22.38636

Table 20: Additional Heat Source Temperature with Produced Flow Rate (90°C)

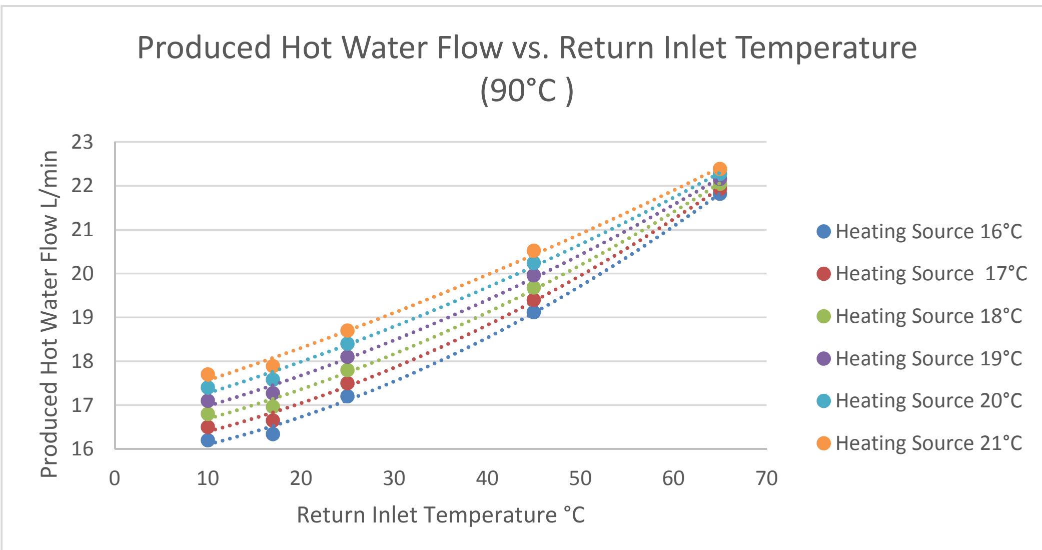


Figure 65: Produced Hot Water Flow vs. Return Inlet Temperature (90°C)

5.3 Example Results – Kincardine Analysis and Feasibility

The demand data specified above is given from the biomass heating tool, and shows an average value for space heating and hot water at a town such as Kincardine. As mentioned above the amount of properties calculated were drawn from the population of the town against the average number of occupants per home. The 500 homes selected were then broken down into the most typical houses found at the town, with the specified amount of bedrooms per property. The tool calculated a round figure for average heating load, peak heat load, energy consumption at design day and annual energy consumption. From this calculation, we can gather the amount of heating required and the amount of heat pumps required to match the demand levels of the town. Heating capacity and power consumption has been taken from the data above. Costing has been calculated for daily energy demand and supply. A return line temperature of 25°C is considerably low and for a combined DHW and space heat system, the return temperature could be much higher. For this analysis the following assumptions have been made;

- Heat pump for duration of the day works at full capacity
- COP is taken as a steady value and fluctuations in return temperature are neglected
- Dynamic parameters (noted in above chapter) are neglected for demand profile
- Steady state conditions are assumed for town demand profile (average values)
- Price per kWh is taken as an average UK value for electricity and other fuel types
- The initial cost analysis neglects any capital cost on the open/closed loop system entering and exiting the heat pump house (district network)
- Losses in the system and efficiencies are neglected
- Number and type of properties at Kincardine are assumed
- Inlet conditions taken at 22°C
- Return Water conditions from incoming pipe network 25°C

HEAT PUMP CONDITONS

Heat Pump: Eco-cute Water Source Heat Pump

Water Source Temperature from condensers = 22°C

Inlet Flow rate to heat pump = 30L/min

Return line water temperature to Evaporator in heat pump = 25°C

Temperature of hot water produced = 90°C

Flow rate of produced hot water from single pump =19L/min

Heat pump heating capacity = 85kW

Power Consumption of Compressor = 26.6°C

Daily heating capacity per day = 2040 kWh/day

Demand profile and number of pumps

Energy Consumption at design day = 51,558 kWh

Average heat demand at design day = 2148kW

Peak demand at design day = 2700kW

Pump Requirement = $\frac{51558\ kWh}{2040\ kWh}$ = 25 Heat Pumps

Cost Analysis

Heat pump consumption per day = 638kWh

25 Pumps consumption per day = 15960kWh

Average Price per unit of electricity = 13.52p/kWh

Cost of Running heat pumps per day = £2157

Average price per home for heating and hot water (using heat pump)

= $\frac{£2157}{500} = £4.30\ per\ day$

5.3.1 Price Comparison for Various Fuels

The section above describes a simple and effective method by which to calculate the daily cost of running the heat pump system for the Kincardine area. As mentioned above, the total amount of heat pumps required (neglecting system and pump losses) is calculated from the total energy demand from the town divided against the heating capacity of the heat pump under certain parameter conditions. It is clear that the Eco-cute heat pump is technically viable heat recovery method, however in terms of Longannet power station the cost associated with the running of the pumps may not be economically viable for the residents of the town. The costs listed above only show a comparison of the varying COP values for a single heat pump, neglecting all other costs. In order to understand the economic feasibility of the heat pump study, a simple comparison of the fuel bills paid by each customer is essential to see if there could be any savings made on the heat pumps against current conventional fuel types used in standard properties. The graph below shows a comparison of the four main types of fuel used for heating and hot water against the price of running the heat pump at the conditions stated above. The values for cost per unit of electricity are taken from the energy saving trust, which give simple assumptions and average price per kWh of each respected fuel type. The costs per unit are as follows;

- Gas - 4.21p/kWh
- Electricity – 13.52 p/kWh
- Oil – 6.43 p/kWh
- Wood pellet – 4.40 p/kWh

Heat pump value shown below displays cost for the conditions stated above for water production at 90°C with return temperatures at 25°C. Cost for each property per day has been based on the total price for heat pumps supplying hot water to 500 homes. Under this assumption the total consumption per home is calculated by the total demand shared equally across the design day for each one of the 500 properties listed. This calculates that the energy consumption per home at the design day for heating hot water is on average 103kWh. The graph below shows the price per day using the average demand profile data shown from the biomass tool.

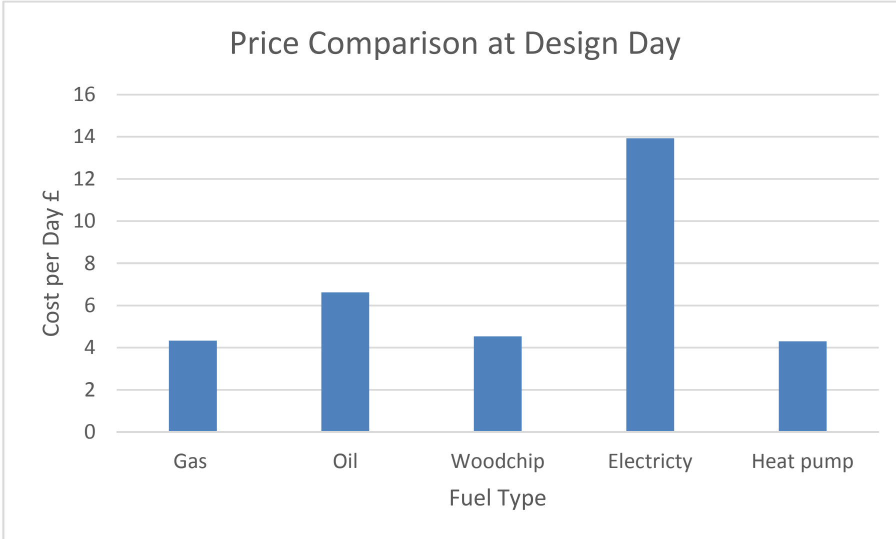


Figure 66: Price Comparison for Different Fuel Types

The graph shows that the in the case of Kincardine and for the conditions stated above it is clear that the cost per day for heating and hot water using the heat pumps at Longannet are too expensive in comparison with gas heating. As mentioned above the analysis does not include any capital costs for the equipment, which in turn would have to be paid by the customer. The reality is that under these conditions for the heat pump is not a viable solution to providing low cost heating to the local town, as the price per unit of gas (even though prices are susceptible to fluctuations) is competitive with cost of running the heat pumps. This analysis also rules out the cost of the heating network itself and the town side equipment for example, water pumps, piping, heat exchangers and central boilers. It is clear however that the potential for a much smaller system or a system that provides hot water to fewer locations or buildings would be a viable solution to heat recovery at Longannet.

5.3.2 Basic Cost Analysis Tool

The performance graphs clearly indicate that the main parameter in maintaining a good COP value is the return water temperature to the gas cooler. The temperature of the water returning through the return line to the heat pump house would have to be as low as possible to maintain a large temperature difference with the CO^2 temperature entering the gas cooler. Again it should be mentioned that the analysis is only for the power station side and all other costs have been neglected at this stage. In the case of Longannet power station water will be fed into the heat pump house either through a closed loop or open loop scheme. Both schemes have been described in the literature review. The main outcome of each scheme is that the closed loop will result in some losses from the number of heat exchangers being used in the outlet flume. It has been assumed that water temperature will already have dropped significantly by the time it passes through the culverts and into the main outlet pumps to the canal. There is also a question of the use of a working fluid for the internal loop in the heat pump house, as the data for the Eco-cute provides data only for water source into the evaporators. In the case of the open loop system, the seawater will pass directly from a pump system either from the culvert line, outlet pumps or a separate pump system in the canal. This water will be fed to a central heat exchanger located in the heat pump house (can be seen in the literature review).

For the purpose of this project and for use in other heat recovery projects, a basic cost analysis tool was created to access the savings gained for both closed loop and open loop systems. The tool can be viewed in the appendix section and is used to calculate a basic cost saving between the heat pump and other fuel types for the demand conditions of Kincardine. The tool incorporates heat pump conditions, where heating capacity and power consumption is used as an input for calculating the total number of heat pumps required and the total daily power consumption. The tool also includes input data for demand side calculation, where the average heat demand can be used to specify the total energy consumption at a particular design day, and where by the average usage per home can be taken from the total amount of homes being assessed in the design area. For this assessment two source temperatures have been specified for open loop (20°C) and closed loop (17°C) with three return loop temperatures into the heat pump house, 17°C, 25°C and 45°C. Demand conditions and assumptions are the similar to the assessment shown above and the graphs below show daily cost of heat pump operation and savings compared to gas heating in the properties listed.

Closed Loop Source 20°C	Return Source Temperature °C		
	17	**25**	**45**
Cost per day per home £	4.13	4.45	5.95
Total daily savings £	0.26	-0.11	-1.61
Total annual savings £	75	-41	-589.45

Table 21: Open Loop Cost Analysis

Closed Loop Source 17°C	Return Source Temperature °C		
	17	25	45
Cost per day per home £	4.25	4.6	6.07
Total daily savings £	0.08	-0.26	-1.73
Total annual savings £	30.69	-95.33	-633

Table 22: Closed Loop Cost Analysis

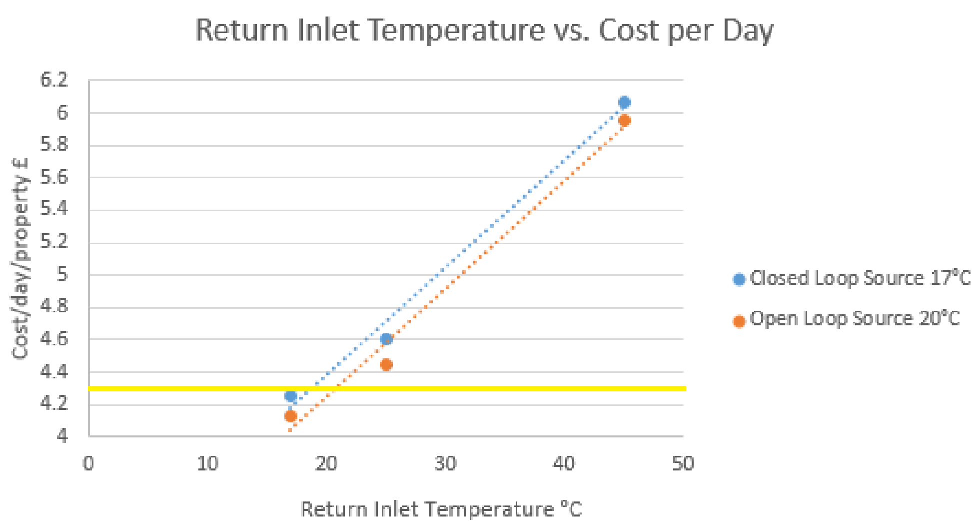


Figure 67: Cost/Day per Property vs. Return Inlet Temperature

As part of this assessment it is ideal to specify a COP value that must be achieved in order for the heat recovery system to be a feasible solution. The yellow line represents the average cost of heating and hot water per day for a typical house in Kincardine. Again it is clear that the most significant influence on cost of running the heat pumps is the return line temperature back to the gas cooler. The graph shows that the difference between a reference open and closed loop temperature is minimal. Ideally under the assumptions stated in the first cost analysis, the return line temperature would have to be maintained below 20°C, which would be a difficult prospect considering some of the current reports and studies suggest return temperatures up to 45°C. Using the basic cost tool values for COP under 3.2 are unsuitable for this particular project. It should be mentioned that the data used neglects any loss in heat over the design loops, and therefore actual COP values would be considerably lower than the stated values. It should be pointed out that the manufacturer’s broacher states up to an operating COP of 8. The example tool that was used can be viewed in Appendix B.

5.4 Heat Recovery – CO² Heat Pumps for onsite use

Longannet has recently modified one of the boiler houses for co-firing biomass and coal. As stated in the initial conclusions, the feasibility of supplying heat offsite is highly undesirable. Solution to this problem could be to use the hot water provided by a small number of heat pumps to an underfloor heating system for drying the biomass onsite, which would cut the cost of pre-drying before coming onsite and any energy used to maintain a low moisture level in storage would be offset. Using the supply onsite would cut costs considerably, where heat pumps, piping and loop pumps could be minimised. Return temperatures back to the gas cooler could also be controlled, which would maintain a high operational performance. Sheffield University studied the use of high temperatures from the flue gas being sued to combine with 90°C cooling water. The cooling water was preheated up to 100°C, where by the steam was used in a belt fed dryer to reduce the moisture content of the biomass woodchips from 1.5 to 0.1 kg-water/kg-fuel. Currently at Longannet the biomass feedstock is dried offsite and stored in a central storage area. If by increasing the storage site, and reducing the need for imported dry biomass, costs could be considerably reduced. More wet biomass could be transferred and stored on site, which would in turn reduce the amount of deliveries (this would be more economically viable and environmentally friendlier). By introducing a drying station onsite, heat lost through the circulating water could be pre-heated to a more appropriate temperature using an Eco-cute heat pump system and transferred to an underfloor heating storage tank or room.

In most cases, biomass drying dryers include some form of passive (forced) or natural heating from air either being fed through a system or by being dried naturally in a storage facility. The biomass energy centre reports that drying systems for biomass will become more appropriate as suppliers who have low supply levels during winter conditions. On site drying would help suppliers to reduce the need for large storage systems for wood and reduce the cost associated. Suppliers could become more adaptable to changing demand markets annually. The costs associated with the initial equipment and systems for drying could then be offset by an expansion in the market and the possibility of other wood fuels to be used for biomass combustion. (Biomass Energy Centre, 2011). The payback on investment would be also offset by additional heating and prices given to Longannet by the feedstock providers. Using a heat pump system would provide significant benefits over using other heating methods such as electrical heating with forced convection systems. The cost of producing the hot water/air needed for conventional heating systems would be much lower when using the Ecocute heat pump, as COP values are suitable for this use.

5.4.1 Characteristics and the effect of moisture content on biomass

The calorific value of biomass is the most important characteristic; that shows the heating potential of the fuel and it also describes the energy content of the fuel. The calorific value of a fuel is given as the amount of heat energy released by a specific amount under complete combustion. The biomass fuel can be either expressed either with a net calorific value (NCV) or gross calorific value (GCV). The main determinant of biomass calorific value is the moisture content, where manufacturers will either display the moisture content of the fuel on a wet or dry basis. (Carbon Trust, 2012) The moisture content of the feedstock biomass has a significant impact on the calorific value of the fuel as the water within the wood has to be evaporated during combustion. Increasing the moisture content of the biomass can have a significant impact on the overall heating value and therefore will affect the energy content of the gases released. For biomass combustion, the biomass feedstock needs low moisture content, however it is important there is some moisture in the biomass for the production of hydrogen. The input energy needed to evaporate this water is called the latent heat of evaporation. As the moisture content of the fuel increases, the latent heat of evaporation increases which in turn decreases the overall net calorific value of the fuel (Biomass Energy Centre, 2011). The graph below displays the linear effect of the effect of decreasing moisture content on the NCV.

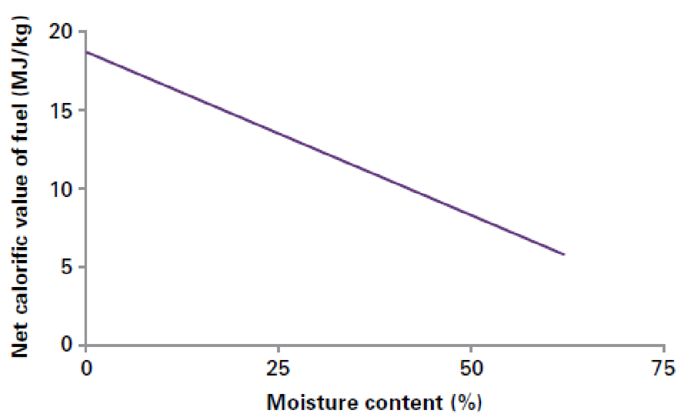


Figure 68: Moisture Content vs. NCV

A forestry commission project stated that the heating value of oven dry tonne of spruce wood is 5.4MWh and for each percent of moisture content increase, the heating value will decrease linearly by 0.0595MWh; (Forestry Commision , 2011)

5.4.2 Potential Benefits of Underfloor Heating systems

Many conventional types of biomass dryers are very costly and complicated and can be very specific with the various biomass fuels on offer. Conventional dryers can be split into two main categories, either by direct contact or indirect contact. For the purpose of this project, the likely drying proposal is for indirect only, where water could be passed through a basic network of plastic piping, where heat is transferred through a heat exchange surface. The use of a transcritical heat pump for water supply may be a viable solution for an indirect heating source; however the cost of running the pump over a specific and set amount of time would have to be weighed against the potential benefit of the reduction of moisture content to achieve a calorific gain. Therefore in order for this type of project to be economically viable the net energy balance between these two parameters would have to be positive. Some of the benefits of underfloor heating systems for conventional purposes have been given below; (Ecovision , 2014)

- The underfloor heating network can be easily designed to suit the needs of various shapes and sizes of buildings, and the use of highly flexible plastic piping allows for heat to be transferred to the wall as well as the floor
- It provides an even heat distribution, and therefor the amount of heat required for underfloor systems is much lower than that of conventional heating types
- The higher the ceiling the more economical the property becomes
- Environmentally friendly when used with renewable heat sources

The advantages of using underfloor heating for drying biomass;

✓ The underfloor heating system is relatively simple for install and maintain and the use of inexpensive material makes it an ideal solution of active heating in a closed environment

✓ The more efficient heat distribution allows for a less expensive means by which to provide heat for the biomass storage house.

✓ Possibility of using lower temperatures for heat distribution, which could improve the operational conditions and the overall running cost of the heat pump by improving the return line temperature.

✓ The system would be environmentally friendly, as the source heat would be provided by a heat pump system, recovering existing low grade heat from cooling water flume.

✓ The efficient underfloor heating system can be easily used for a large (high ceiling) property and therefore would be ideal for a large volume of biomass feedstock.

5.5 Further Work: Basic Outline of Proposed Drying Network

This section describes some of the basic principles for the proposed onsite heat pump network for the transcritical heat pump recovery system. In any case the options open to Scottish Power are wither to supply the water into the heat pump system from a direct open loop scheme or an indirect closed loop system. As mentioned above costs associated with closed loop system would be significantly higher and the temperature drop from the cooling canal to the heat pump evaporator will be much higher than a direct pumping of water from the canal to the pump house. There is a great potential for recovering some of the heat from the circulating water and transferring some upgraded heat to a central onsite location for biomass drying. This would significantly reduce any costs associated with offsite drying and would enhance the energy content of the biomass feedstock. In essence it is possible to increase the energy content of the fuel thus reducing the overall amount needed for combustion per unit of time. Again this would reduce the capital costs of importing and transporting bulk feedstock onto the site. This section provides basic details so that the project could be continued and a detailed set of technical and economic calculations can be carried out to see if the project would be feasible for Scottish Power. Details to the proposed network and the diagram are shown below;

1. As water exits the circulating pumps from the culverts, water is passed downstream in the cooling canal
2. In an open loop scheme, water is fed through an appropriately sized pipe, where water is pumped up to a central heat exchanger, where heat is extracted and transferred to another loop cycle at the heat pump side. Water can also be fed directly through a filter screen and fed into the heat pump pipe network, where water is transferred directly into the evaporator (the effect of sea water on heat pump components must be considered here).
3. Water passes into the inlet of the heat pump evaporator and returns back into an exit loop to be dumped back into the outlet canal
4. A simple pipe network at the gas cooler side passes water through to be heated to upgraded temperatures needed for biomass drying.
5. The pipe network passes along a short distance to biomass central storage containers, where the water is passed through an underfloor heating loop at a flowrate specified by the pump and the requirement for heat transfer to allow sufficient biomass drying.
6. As the water is passed through the storage containers it is then transferred back through the return loop to the inlet of the gas cooler.

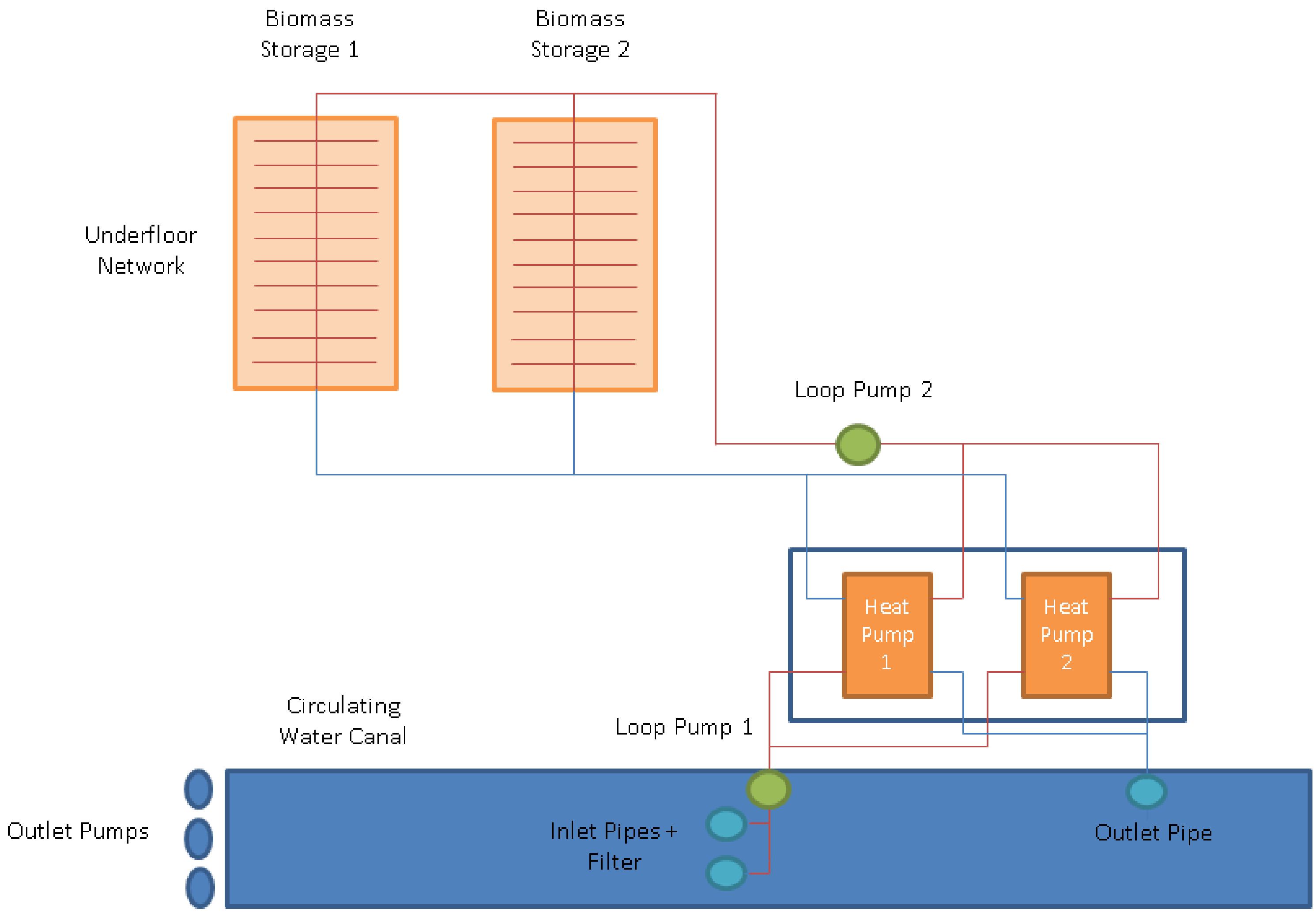


Figure 69: Onsite Proposal Diagram

Chapter 5: Project Conclusions

The assessment above clearly identifies that even at full capacity and efficiencies and losses being neglected, and with regards to the power station side only, the project would be easily classified as a non-viable solution to accessing and recovering some of the heat lost to the circulating water to be utilised at another site. For the cost analysis specified in the latter stages of the project entail only the heat pump house side and does not consider other economical, technical and environmental issues. Again it is clear from the literature review that other technologies are unsuitable for the temperature range at the cooling water outlet and that heat pumps are the only suitable technology that could be applied. It is evident that the ecocute heat pumps could be used for other projects such as drying biomass feedstock in storage compartments through a simple onsite water distribution network. The temperatures of the cooling water should be utilised first before any projects utilise the local sea water temperatures, as there could be a significant benefit to using some of the heat lost in the cooling canal. Some of the major conclusions/issues are listed below;

- Heat loss across the pipe network to the demand site. The long distance from the pump house to the central storage will bring significant losses in heat. During the literature review, it was clear that most district heating schemes are used in conjunction with an onsite CHP, ground source or biomass supply. In the case of Longannet, the supply is offsite which brings many losses both technically and economically
- The analysis uses low return temperatures back to the heat pump to show even at significantly low temperatures the heat pump does not compete well with other fuels and a further analysis would show a considerable drop in COP and an increase in cost.
- The location of Longannet is highly unsuitable for providing the supply of heat to a named demand site. The three example areas shown in the data collection section, show that there is a wide mix of buildings varying from non-commercial to commercial properties. One major issue for introducing a district heating network is the disruption to the local area and the demand site. It would be ideal to have a series of new properties i.e. a new housing estate, block of flats or a new residential area located around Longannet so that disruption could be minimal.
- With reference to both the economic and technical side, open loops schemes should be looked on favourably against closed loop schemes. In closed loops schemes, the cost

would be considerably higher and the temperature loss from the canal to the heat pump house would be much greater than an open loop scheme.

- The major problem with the project and the heat recovery at Longannet is that there is a sufficient supply and technically CO^2 heat pumps provide a good means by which to recover heat, however its economic performance is very poor in comparison with average gas prices. An ideal case would have a number of related properties linked to a central storage accumulator or tank, however considering the high capital cost associated with a district heating scheme and the heat pumps supplying these buildings with a new gas installation would be both more technically and economically viable
- The main consideration to be taken into account is the short lifespan of Longannet and the future of conventional power stations. From the initial assessment of Longannet it is clear that the power plant is currently striving towards improving operating efficiency and lowering emissions but the future of the plant is uncertain. It is clear that any heat recovery system supply would have to be used directly on site rather than off-site. In the case that the project would be delivered, decommissioning of the system would have to be considered as Longannet nears its end life.
- The industrial site at Falkirk could be a viable solution to meeting supply with demand. The DECC tool displays a very high demand for heating at this particular site. The tool also displays that the Falkirk industrial site has the highest demand profile for the North-East of Scotland. This could be a serious possibility, as the pipe network would be cheaper and less distributive to local residents of Grangemouth and Kincardine. In this case a single loop could provide heating to a fewer but much larger heat exchangers or hot water tanks. Again the company would have to weigh up the price of heating against the price from a heat pump network. Again, when including capital costs at supply and demand side, the project would be deemed non-feasible.
- The project may be ideal for another smaller project (similar to heat recovery systems shown in Chapter 3) for hotels or single block housing estates or housing communities. The project may also be more feasible when introduced into planned housing developments rather than existing developments. In any renewable project, energy efficiency in each individual property is more important and should be considered before any renewable technology is integrated. For example in the local area, the houses are very old and are most likely badly insulated and would be unsuitable for renewable projects.

Appendix A

Heat source °C		Capacity kW	Inlet Water Temperature				
Inlet	Outlet		10°C	17°C	25°C	30°C	40°C
36	32	Heating	116	111	102	96	84
		Power	21.6	22.2	24.2	24.5	26
22	17	Heating	106	101	93	87	74
		Power	22.5	23.1	24	24.3	25.6
12	7	Heating	86	82	76	72	62
		Power	21.2	21.8	23.2	23.8	24.4
-5	-9	Heating	52	50	46	43	39
		Power	17.3	18.4	18.2	18.8	19.7

Table 23: Heating Capacity vs. Return Inlet Temperatures (65°C)

Heat source °C		Capacity kW	Inlet Water Temperature				
Inlet	Outlet		10°C	17°C	25°C	45°C	65°C
36	32	Heating	108	101	93	71	40
		Power	27.3	26.7	26.9	27.1	27.2
22	17	Heating	105	92	85	64	39
		Power	27	26.4	26.6	27	27.1
12	7	Heating	83	76	71	56	35
		Power	24.8	24.9	24.9	25.3	25.7
-5	-9	Heating	50	48	38	28	21
		Power	19.4	19.6	19	16.6	20.2

Table 24: Heating Capacity vs. Return Inlet Temperatures (90°C)

Heat source °C		65°C	Inlet Water Temperature				
Inlet	Outlet		10°C	17°C	25°C	30°C	40°C
36	32	Flow rate L/min	19	20	21	22	23
22	17	Flow rate L/min	18	18.2	19	20.8	22.5
12	7	Flow rate L/min	15	15.1	16	18	20
-5	-9	Flow rate L/min	9	9.2	8.8	9	12

Table 25: Flow Rate vs. Return Inlet Temperatures (65°C)

Heat source °C		90°C	Inlet Water Temperature				
Inlet	**Outlet**		**10°C**	**17°C**	**25°C**	**45°C**	**65°C**
36	**32**	Flow rate L/min	19	20	21	22	23
22	**17**	Flow rate L/min	18	18.2	19	20.8	22.5
12	**7**	Flow rate L/min	15	15.1	16	18	20
-5	**-9**	Flow rate L/min	9	9.2	8.8	9	12

Table 26: Flow Rate vs. Return Inlet Temperatures (90°C)

Heat source °C		65°C	Inlet Water Temperature				
Inlet	**Outlet**		**10°C**	**17°C**	**25°C**	**30°C**	**40°C**
36	**32**	Power Consumption kW	21.6	22.2	24.2	24.5	26
22	**17**	Power Consumption kW	22.5	23.1	24	24.3	25.6
12	**7**	Power Consumption kW	21.2	21.8	23.2	23.8	24.4
-5	**-9**	Power Consumption kW	17.3	18.4	18.2	18.8	19.7

Table 27: Power Consumption vs. Return Inlet Temperatures (65°C)

Heat source °C		90°C	Inlet Water Temperature				
Inlet	**Outlet**		**10°C**	**17°C**	**25°C**	**45°C**	**65°C**
36	**32**	Power Consumption kW	27.3	26.7	26.9	27.1	27.2
22	**17**	Power Consumption kW	27	26.4	26.6	27	27.1
12	**7**	Power Consumption kW	24.8	24.9	24.9	25.3	25.7
-5	**-9**	Power Consumption kW	19.4	19.6	19	16.6	20.2

Table 28: Power Consumption vs. Return Inlet Temperatures (90°C)

Appendix B

HEAT PUMP COST PROFILE ANALYSIS

Heat Pump Conditions		
Parameter Conditions	Units	Value
Heat Pump	-	ECO-CUTE water source
Water Source Entry Temperature	°C	17
Inlet Flow Rate to Evaporator	L/min	30
Return line Water Temperature to Gas Cooler	°C	17
Temperature of Hot Water Produced	°C	90
Produced Hot Water Flow Rate	L/min	19
Pump Heating Capacity	kW	106
Power Consumption of Compressor	kW	33
Heat Pump COP	-	3.212121212
Daily Energy Consumption	kWh	792
Annual Energy Consumption	kWh	289080

Basic Cost Analysis		
Parameter Conditions	Units	Value
Total Energy Produced per heat pump	kWh	2544
Total Energy Consumption of pumps required	kWh	16049.20755
Cost of running x number of heat pumps per day	£/day	2169.85286
Average Price for heating/hot water from pumps per home	£	4.339705721

Savings Using Heat Pump	£/day	0.000972679
	£/year	0.355027925

Demand Profile		
Parameters	Units	Value
Area	-	Kincardine
Number of Properties	-	500
Energy Consumption at Design Day	kWh	51552
Average Heat Demand at Design Day	kW	2148
Peak Demand at Design Day	kW	2700

Parameters	Units	Value
Average Household Energy Consumption	kWh	103.104
Cost per unit of Fuel used	£/kWh	0.0421
Daily Cost for heating and hot water	£/day	4.3406784

Number of Heat Pumps Required	20.26415094

Fuel Type for Heating	Cost per Unit £/kWh
Electricty	0.1352
Gas	0.0421
Oil	0.0643
Wood Pellet	0.044

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