DEPARTMENT OF MECHANICAL & AEROSPACE ENGINEERING

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Investigating the Potential of Low Exergy Thermal Sources to Improve the COP of Heat Pumps

Author: Brian Gillan

Supervisor: Dr. Daniel Costola

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Signed: Brian Gillan

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Abstract

The purpose of this dissertation was to investigate the potential of low exergy thermal sources to improve the coefficient of performance of heat pumps, due to a global desire to improve the efficiency of renewable technology and reduce energy consumption. After reviewing existing literature, it was decided to focus on anthropogenic low exergy thermal sources with air source heat pumps as there appeared to be a relative lack of research in this area.

A number of air source heat pumps were analysed to determine if sensitivity to source temperature changes was consistent across all selected manufacturers and models. It was determined that there was a high degree of variation in sensitivity, with air-to-water heat pumps being overall more sensitive than air-to-air heat pumps. It was also determined that whilst some heat pumps were more sensitive in a low temperature range, others were more sensitive in a medium temperature range. This finding indicated that the climate within which it is operating will be a major factor when choosing a heat pump to use.

Having selected a heat pump with an appropriate degree of sensitivity, schematics were created indicating, showing theoretical configurations in which the heat pump could be installed within a building. The relevant calculations were then performed to calculate the potential COP improvements that could be achieved. It was found that by utilising 20°C indoor air, vented directly to an air mixer feeding the evaporator unit, and waste heat from the compressor, a maximum COP increase of 23% could be achieved, resulting in an energy saving of approximately 18%.

Acknowledgements

I would like to thank my supervisor, Dr Daniel Costola, for his encouragement and assistance throughout this project. The ability to bounce ideas off him at our weekly meetings kept me on track and moving forward at a good pace.

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Nomenclature

COP	Coefficient of Performance
C_{Air}	specific heat of air, *J/kg°C*
E_C	Waste energy from the compressor, *kW*
HR_{Eff}	heat recovery efficiency
P	pressure
Q_B	air flow rate of building fan
Q_E	air flow rate of evaporator fan,
Q_{Output}	heat output from heat pump, *kJ/kg*
SCOP	Seasonal Coefficient of Performance
SPF	Seasonal Performance Factor
T_I	indoor temperature, *°C*
T_O	outdoor temperature, *°C*
T_{sink}	temperature of heat sink, *K* or *°C* as defined
T_{source}	temperature of heat source, *K* or *°C* as defined
V	volume
W	work input, *kJ/kg*
ρ_{Air}	density of air, kg/m^3
ΔCOP	COP difference
ΔT	temperature difference, *K* or *°C* as defined
ΔT_s	source temperature difference

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1. Introduction

1.1. Problem Definition

In response to climate change and a desire to provide energy using renewable sources driven by fossil fuel depletion, many countries worldwide including those within the European Union and the United States of America are required to reduce their energy consumption whilst focusing on improving their use of renewable energy sources (European Commission, 2014, United States Government, 2013). The majority of renewable sources are, at present, focused on electricity generation instead of heat provision. An exception is biomass usage which is capable of being used in combined heat and power systems (U.S. Energy Information Administration, 2016b, Scottish Government, 2015). There are studies by authors such as Ghosh (2016) and Weldu and Assefa (2016) which question the sustainability of large scale biomass usage therefore it is important to look at other renewable heat sources one of which is heat pumps.

The performance of heat pumps is expressed by the coefficient of performance (COP) which is analogous to efficiency and is influenced by the difference in temperature between the heat sink and heat source of the heat pump. Reducing the difference in temperature between the heat sink and the heat source, by increasing the temperature of the heat source can lead to an increase in the COP of the heat pump. Increasing the COP of the heat pump by increasing the source temperature could potentially be achieved by using low exergy thermal sources from the environment in which it is installed. Using the surrounding environment together with the heat pump is one of the ideas promoted by the IEA Heat Pump Centre (2016) which states that heat pumps rely on the principles of efficient use of renewables and efficient end-use, therefore it is important to investigate the potential of using low exergy thermal sources in this manner. The use of low exergy thermal sources and heat recovery from urban facilities have both been subjects which the European Commission has requested be investigated (European Commission, 2016b, European Commission, 2016c).

Low exergy thermal sources can be separated into two categories; anthropogenic and natural. Natural low exergy thermal sources, such as solar energy, have previously been used in studies by Elliott (2013), Emmi et al. (2015), Suleman et al. (2014) and Kuang and Wang (2003) to raise the source temperature of heat pumps and show that this results in an increased COP. Whilst there are many papers detailing the use of natural low exergy sources to improve heat pumps, this author found a relative lack in reports investigating the use of anthropogenic sources in the same manner. Anthropogenic low exergy thermal sources are readily available within buildings (Carbon Trust, 2016). The availability of low exergy thermal sources was also stated by Wang and Ma (2015) who also went on to state that the beneficial use of heat pumps depends on the interaction between the heat pump and the building. It is therefore deemed of interest to determine how the interaction between the heat pump and the low exergy thermal sources from the building could occur and what impact this would have on the coefficient of performance of the heat pump.

1.2. Aim

The aim of this dissertation is investigate what potential there is for low exergy thermal sources to be used in order to increase the coefficient of performance of heat pumps, and how the installation of heat pumps in buildings could include the integration of existing systems in order to make use of their low exergy thermal outputs.

1.3. Objectives

1. Identify low exergy thermal sources from existing building systems which could be used to input heat into a variety of heat pumps.
2. Investigate a variety of heat pumps, comparing how sensitive the coefficient of performance is to changes in source temperature
3. Using the heat pump determined to be most sensitive, calculate the theoretical impact on the COP when the source temperature is altered by various combinations of low exergy thermal sources.
4. Using the results of the calculations, discuss how building systems could be combined so that they work in harmony and be used to improve the performance of heat pumps.

1.4. Outline of Methodology

This section outlines the methods which were used throughout the various stages of the project.

The first stage was to perform a literature review to ensure that no similar investigations had previously been performed and also to gain an understanding of the various elements involved in the project. The project involved using low exergy thermal sources to improve the coefficient of performance of heat pumps therefore it was necessary to gain an understanding of the theory of heat pumps, particularly regarding the Carnot Cycle and how it impacted the coefficient of performance. Given that exergy sources were also to be identified and used to improve the coefficient of performance of the heat pump, it was also deemed necessary to gain an understanding of exergy and the theory behind its ability to improve a heat pump.

Exergy is the ability to provide work to a system. An exergy source can be either naturally occurring (e.g. solar power, geothermal vents) or anthropogenic (e.g. boiler flue gases). Anthropogenic low exergy thermal sources were focused on due to an abundance of existing literature regarding the use of natural exergy sources and a relative lack of literature on anthropogenic sources. It was identified that most exergy sources which occur within buildings were anthropogenic in nature, with the majority of identified systems ejecting heat in the form of waste air. As a result of these findings, it was decided to focus on air source heat pumps.

Air source heat pumps are manufactured by a number of companies and can be either air-to-air or air-to-water type heat pumps. Both types of air source heat pumps come in a variety of specifications primarily identified by their nominal heating capacities and nominal power inputs. In order to compare air-to air and air-to-water heat pumps, theoretical sensitivity studies were performed, using Excel, to determine how the COP of each heat pump reacted as the source temperature was altered. The rate at which the COP of each heat pump changed per degree of source temperature change was then calculated in order to define the sensitivity of each heat pump. Firstly, the overall sensitivity of each heat pump was calculated before the sensitivities within the low, medium and high source temperature ranges were determined. It was important to determine if there were any particular ranges in which the heat pumps were most sensitive as this may have identified which type of climate each heat pump would be most effective in. After comparing each type of heat pump and determining their respective sensitivities, a comparison was performed between heat pumps with a low nominal heating capacity and those with a high nominal heating capacity to determine whether the designed nominal heating capacity had an influence on the sensitivity of the heat pump.

Once the sensitivity analysis was completed, one particular heat pump was selected, due to its high degree of sensitivity across a number of temperature ranges, for use in further calculations. The calculations for which the selected heat pump was used were to define combinations in which the heat pump could be installed to make use of low exergy sources in the surrounding environment. For each combination of installation, a schematic was also drawn to give a simplistic visual representation of the installation. For each combination, the percentage improvement in COP at selected source temperatures was calculated when the low exergy sources were included, from which the most effective combination was determined.

After all calculations on heat pump sensitivity and installation effectiveness were completed, discussions were undertaken to highlight the important results of the calculations. The future works which could be undertaken to follow on from the results of this investigation were also discussed.

2. Literature Review

2.1. Introduction

This literature review covers the main elements of this project such as the theory of heat pumps, the Carnot Cycle, coefficient of performance, exergy and low exergy thermal sources. Before delving into these elements of the project, a more complete understanding of why renewable energy sources and renewable heat sources in particular are being studied was required.

The most prominent reason for researching renewable technology is climate change. Climate change is a major global concern, the evidence and effects of which are being highlighted by organisations such as the United Nations (2013), NASA (2016) and the European Commission (2016a). The European Commission (2014) passed a directive in 2010 which stated that by 2020 all new buildings need to be energy efficient to reduce energy consumption, with the remaining energy demand able to be supplied through renewable sources, be they on or off-site. This directive came as a result of the awareness that many of the causes of climate change were anthropogenic in nature, particularly the use of fossil fuels to provide energy (Cubasch et al., 2013). In an attempt to reduce their use of fossil fuels, the President of the United States directed The Department of the Interior to issue permits for 10 gigawatts of renewable energy on public lands by 2020 which added to the 10 gigawatts they previously permitted in a similar directive in 2012 (United States Government, 2013).

Increasing the use of renewable energy sources alone will not solve climate change issues due to the ever increasing usage of energy. According to the U.S. Energy Information Administration (2016a), the residential sector for European countries in the Organisation for Economic Co-operation and Development (OECD) region will experience an energy consumption increase of approximately 0.9% per year between 2012 and 2040, while the commercial sector for the same area experiences an increase of approximately 1.3% per year between 2012 and 2040. It is also stated that the growths in OECD Europe is greater than in the United States by 0.7% and 0.6% for the residential and commercial sectors respectively.

When considering the United Kingdom as an individual country, it is predicted that final energy demand will reduce in the forthcoming years until around 2025 before returning to current levels by 2033 then continuing to increase. The reason for this trend is that demand in the industrial sector is expected to fall but the domestic sector is expected to start increasing around 2030 (Department of Energy & Climate Change, 2015). This shows that whilst energy efficiency is a large focus for new buildings, it will still be competing against an increasing demand which means that it will be important to continue ensuring that there are enough energy sources to meet this increased demand.

With the requirement for renewable energy generation continually increasing, it is important to look at the current breakdown of renewable sources. The majority of renewable energy generation within the United States of America comes from biomass, followed by hydro and wind, with only minor generation coming from geothermal and solar photovoltaic sources, which equates to approximately 13% of electricity generation for the country (U.S. Energy Information Administration, 2016b). When it comes to renewable sources in Scotland, generating renewable electricity appears to be much easier and widespread than generating renewable heat using existing technology. Statistics from the Scottish Government (2015) state that 44.4% of electricity is currently supplied by renewable sources however only 3% of heat is supplied by renewable sources. Based on that information, it can be determined that renewable heat is the far behind renewable electricity with regards to its level of use. In order to promote more widespread use, and for the purposes of this report, improving efficiency in existing technology such as heat pumps must be considered.

2.2. Heat Pumps

2.2.1. Heat Pump Benefits

As mentioned, one of the primary renewable heat technologies available for use in buildings is that of heat pumps, which come in a variety of types such as air source, ground source, water source and sewage (waste water) source. Heat pumps are classed as renewable despite the fact that they require an electrical input to operate, which may or may not be from a renewable source. It should be noted that some ground source heat pumps which go to large depths are not strictly renewable as they operate using decaying radioactive isotopes in the ground, however given that the decay process is very long they can be classed amongst renewable heat pumps (Elliott, 2013).

Some benefits of using heat pumps (Energy Saving Trust, 2014):

- Lower fuel bills, especially if you are replacing conventional electric heating
- Potential income through the UK government's Renewable Heat Incentive (RHI)
- Lower home carbon emissions, depending on which fuel you are replacing
- No fuel deliveries needed
- Can heat your home as well as your water
- Minimal maintenance required

2.2.2. Heat Pump Operation and the Carnot Cycle

With regards to the operation of a heat pump, it can best be described graphically as shown in Figure 1 where it can be seen that the heat from the source is used to evaporate the fluid in the pipe as it passes through the evaporator, before passing through the compressor. By increasing the pressure of the gas in the pipe the temperature of the gas increases. The gas is then passed through a condenser which, in the process of condensing the gas into a fluid, causes the heat to be ejected into the heat sink. The fluid in the pipe then passes through an expansion valve and back into the evaporator so that the process can start all over again.

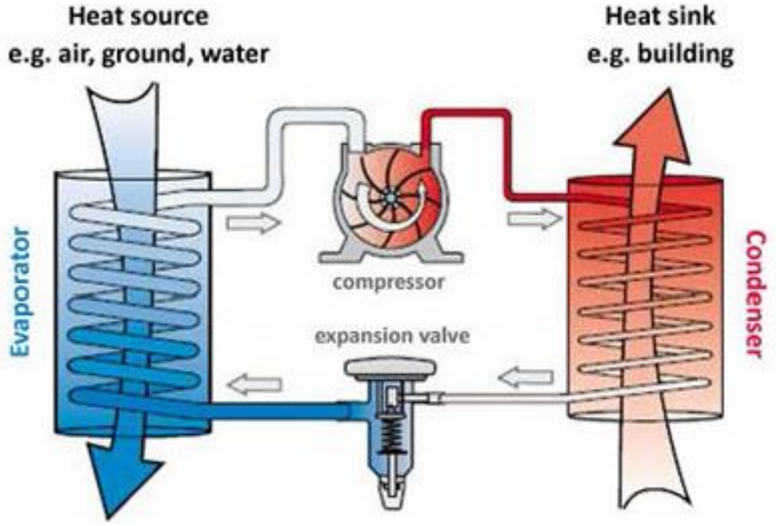


Figure 1. Graphic representation of a heat pump cycle (South West Agricultural Resource Managment Knowledge Hub, 2013)

The process which takes place in a heat pump is known as the Carnot Cycle, a diagram of which is shown below. It is important to be aware of the elements within the Carnot Cycle as they directly relate to the coefficient of performance of the heat pump.

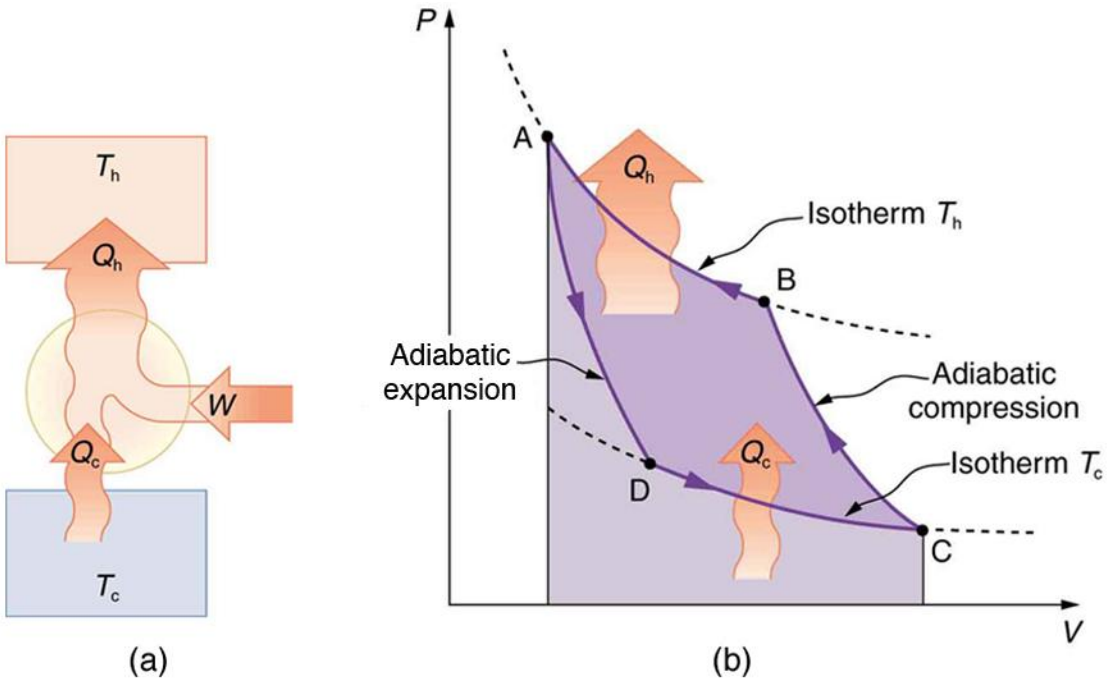


Figure 2. (a) Schematic diagram showing heat transfer from a cold reservoir to a warm reservoir with a heat pump, (b) PV diagram for a Carnot cycle (RICE University, 2016)

Part (a) of Figure 2 highlights how the work input to the heat pump is used to transfer the heat from the cold reservoir (heat source) to the hot reservoir (heat sink). Relating this back to Figure 1, the work input would be the work performed by the compressor. Part (b) is a pressure-volume diagram that shows the relationship between pressure, volume and temperature which was mentioned above when discussing Figure 1.

2.2.3. Coefficient of Performance (COP)

This conversion efficiency of a heat pump is referred to as its Coefficient of Performance (COP) and is calculated using the formula:

$$COP_{\text{heat pump}} = \frac{Q_{\text{output}}}{W_{\text{electrical}}} \quad (1)$$

Equation (1) shows that the COP of the heat pump is calculated by dividing the amount of heat output from the system by the amount of electrical work input into the system. The greater the amount of heat output from the system naturally increases the COP of the system if the electrical input stays constant. The test procedure for calculating the COP of heat pumps is dictated by EN 14511 which defines the boundary conditions which must be adhered to (Klein, 2012). It is important that all manufacturers are required to test under the same conditions as it means that all figures used in data sheets can be compared in the knowledge that any differences are down to the specifications of the heat pumps and not the conditions they were tested under.

Some manufacturers state on their website that heat pumps are around 300% efficient (Daikin, 2016a), whilst Elliott (2013) states that this is only a theoretical potential and that adverse weather conditions could mean that the heat pump does not generate three times the energy value of electricity input to make it operate. Whilst many heat pumps routinely achieve this level of efficiency, the key point to remember is that adverse conditions could reduce efficiency. It should also be noted that the efficiency discussed is the conversion efficiency of the heat pump, not the thermal efficiency.

The thermal efficiency of a heat pump is known as the Carnot COP of the heat pump which is used to determine the maximum theoretical COP possible. The Carnot COP can be calculated using the following equation, ensuring that all temperature values are in Kelvin (K):

$$COP_{heat\ pump,Carnot} = \frac{T_{sink}}{T_{sink} - T_{source}} \tag{2}$$

It can be seen from Equation (2) that in order to maximise the COP of the heat pump, the temperature difference between the heat sink and the heat source must be minimised. The avenue explored in this project is to use an external thermal source to raise the source temperature so that it is closer to the temperature of the sink.

Whilst the coefficient of performance indicates the efficiency of a heat pump at a given temperature, a more accurate representation of the heat pump efficiency is known as the seasonal coefficient of performance (SCOP) or seasonal performance factor (SPF) (Heat Pump Association, 2014). The SCOP is a representation of the COP of the heat pump taking into account the variations in efficiency over a period of time caused by fluctuations in temperature (Daikin, 2016b). The SCOP of a heat pump is calculated according to the European Standard, EN 14825, with a requirement to calculated the SCOP for the average climate of Strasbourg whilst it is voluntary to calculate the SCOP for the warmer and colder climates of Athens and Helsinki respectively (Rasmussen, 2011).

2.3. Exergy

Exergy is the ability of a system to produce work as it moves into thermodynamic equilibrium with its surroundings (Gundersen, 2011). During the operation of a system, the exergy, unlike energy, can be destroyed thus the exergy leaving is diminished compared to that entering the system as shown in Figure 3, below:

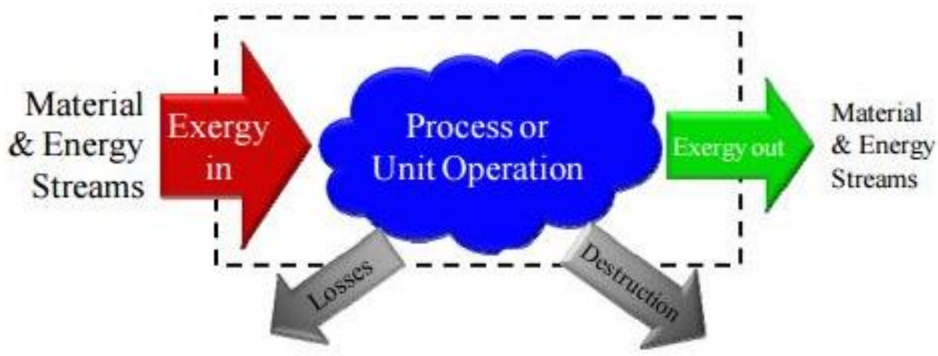


Figure 3. Exergy flows entering and exiting a Process or Unit Operation (Gunderson, 2011).

It is important to note that Dinçer and Rosen (2012) have stated that exergy can be input into a system thereby increasing the exergy of that system. If the exergy leaving a system is in the form of heat, it could be theorised that by inputting this into another thermodynamic process such as a heat pump, it could improve the exergy of that system. Regarding the form of exergy sources, it was found that they could come from many places such as external exergy resources (natural resources, e.g. solar energy) or waste exergy emissions from anthropogenic processes (Dinçer and Rosen, 2012).

2.4. Using Natural Exergy Thermal Sources with Heat Pump Systems

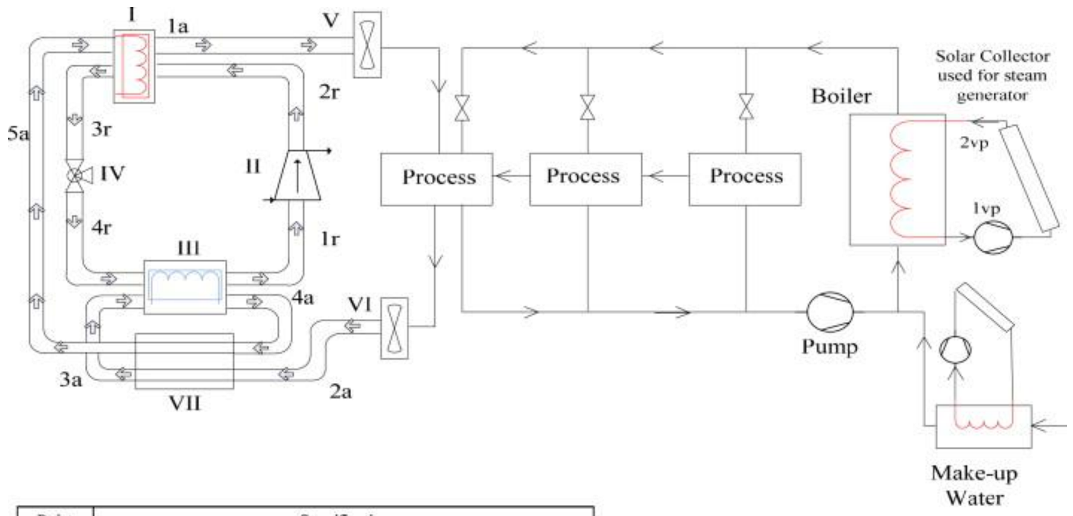
It has been found that natural exergy sources are the most commonly used alongside heat pumps, namely solar and geothermal resources. Typically, these sources are considered to have a finite thermal capacity due to the fact that boreholes degrade over a number of years and there is lack of solar energy during the night.

As mentioned earlier, it is possible to use exergy sources to assist the operation of heat pump systems, however investigation into this has so far been limited to using natural exergy sources to compliment heat pumps as shown by Scarpa and Tagliafico (2016), instead of using them to improve the COP of the heat pump. These authors investigated how direct-expansion solar assisted heat pumps could be improved by utilising condensation which occurs on the solar collector if it is kept under the dew point temperature. It was found that the temperature of the solar collector had to be optimised to balance the energy generated through the condensation process against the COP of the heat pump because the COP would be negatively affected as the temperature of the solar collector was decreased.

Likewise Cho (2015) utilised solar energy as a low exergy thermal source by attaching a solar collector to a heat pump system. In this instance, when conditions were appropriate, the system used direct solar heat without requiring to use the heat pump. In essence, the heat pump was a back-up system in the arrangement, so the natural exergy source could not be considered to have an effect on the COP of the heat pump.

An integrated solar heat pump system, as shown in Figure 4, was studied by Suleman et al. (2014) which incorporated both a solar collector and a heat pump in two systems, linked through a heat recovery unit, which fed into the heat pump. Initially the solar generated heat was used for various processes, with the heat degrading each time, however at the last process the waste heat was recovered and increased by the heat pump in order to be fed back into this last process.

The system was in essence utilising a low exergy thermal source to increase the temperature of the air feeding into the heat pump. When considering the COP of the heat pump, variations were made to the ambient air temperature and the temperature at the condenser, however no studies looked at how the COP of the heat pump could be affected by a change in the temperature generated by the solar collector, especially over a sustained period of time.



Point number	Specification
1a	Hot air leaving the condenser (Supply Air)
2a	Inlet air entering the heat recovery unit
3a	Air entering the evaporator
4a	Cool air leaving from evaporator
5a	Inlet air to condenser
1r	Saturated refrigerant entering the compressor
2r	Refrigerant at high temperature and pressure entering the condenser
3r	Condensed liquid refrigerant leaving the condenser
4r	Outlet of expansion valve
1vp	Inlet of circulation pump
2vp	Heated heat transfer fluid from solar collector

I Condenser
II Compressor
III Evaporator
IV Expansion Valve
V Supply Fan
VI Suction Fan
VII Heat Recovery Unit

Figure 4. Heat pump system using heat recovery from solar generated steam cycle (Suleman et al., 2014).

One study which was found to analyse how solar heat could be used to raise the temperature of water being used as the source for a water source heat pump was undertaken by Kuang and Wang (2003). The experimentation period for the heat pump occurred under the worst seasonal conditions for that area, so they were able to determine whether the heat pump would work when it was most required. Through their experiments, they concluded that under their specific conditions an auxiliary energy source was required to aid the solar collector as the solar heat was not sufficient to keep the water in the storage tank within the required temperature range. Unfortunately, when measuring the effect on the COP, the experiment relied on the condensing temperature changing due to the auxiliary heat source keeping the evaporating temperature relatively stable. This meant that whilst it was shown in Figure 6 that the COP of the heat pump improved as the temperature difference reduced, the actual effect of the solar heat could not be properly assessed.

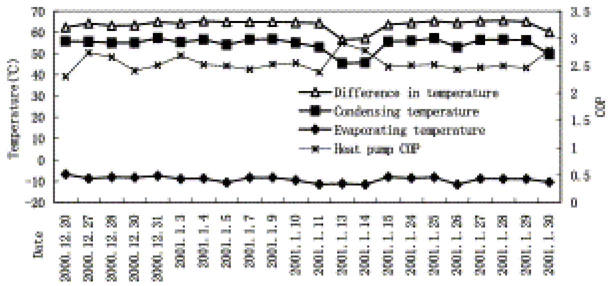


Figure 6. COP of heat pump compared to temperature difference.(Kuang and Wang, 2003)

Solar assisted ground source heat pumps were studied by Emmi et al. (2015) in order to determine whether the efficiency of ground source heat pumps could be improved by pumping excess solar thermal energy into boreholes. They used TRNSYS in order to use computer simulations to investigate how the heat pump would operate in cold climates, taking into account the building requirements throughout. The simulation involved an identical building being investigated in six different climates. Certain other elements of the model were constant throughout the six scenarios such as the size of the water storage tank and solar collectors whilst variable elements included the type of heat pump used and total length of the boreholes.

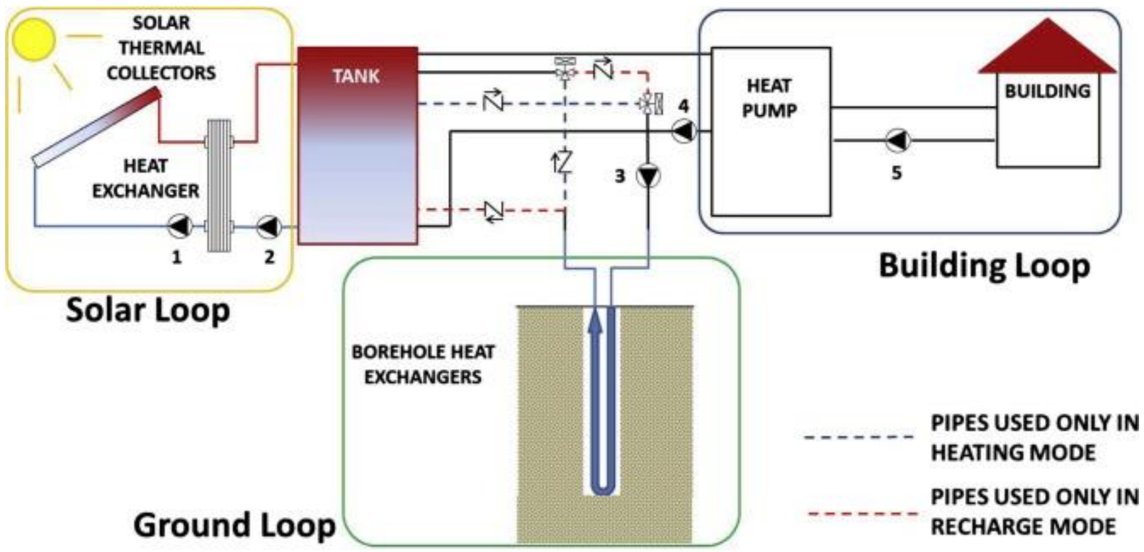


Figure 5. Solar thermal assisted ground source heat pump (Emmi et al., 2015).

As shown in Figure 5, the system was set up so the solar heat could raise the temperature of the water within the storage tank which was coupled with the heat exchangers in the ground source heat pump. If there was insufficient solar heat, the ground source heat pump could operate on its own to provide heating. Likewise, if heating was not required within the building, the loop could be closed so that the solar thermal heat could be pumped down into the borehole. The system also had a free-heating control within it so that if the required temperatures were reached, the heat pump could be bypassed. The reason for these controls was to minimise the exergy usage within the system as a whole, therefore increasing its efficiency.

The system can only be considered to improve the COP of the heat pump however if the solar thermal source is being used to raise the temperature in the water tank before it is passed through the heat pump. The result most relevant to this project coming from the TRNSYS simulation was the direct comparison between a regular ground source heat pump and the solar assisted ground source heat pump. The results showed that at the tenth year of the simulation, the COP of the solar assisted ground source heat pump was between 7% and 27% higher across the different climates when compared to the normal ground source heat pump. This indicates that supplying exergy in the form of thermal heat does have a positive effect on the COP of the heat pump.

A study by Bellos et al. (2016) involved using TRNSYS to review the effect on both air source and water source heat pumps if solar energy was used to assist the system. With regards to the air source heat pump, the solar energy is solely used to power the heat pump, minimising the amount of energy required from the grid, however with the water source heat pump, heat is generated at the solar collector and supplied to a water storage tank which in turn feeds the water source heat pump. For the water source heat pump, two types of system are tested, the first featuring flat plate collectors and the second using photovoltaic panels.

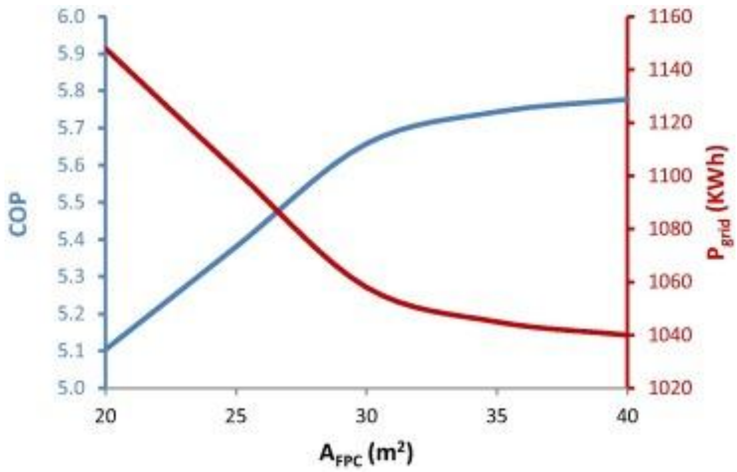


Figure 7. COP of water source heat pump and electricity consumption from grid for the examined FPC areas.(Bellos et al., 2016)

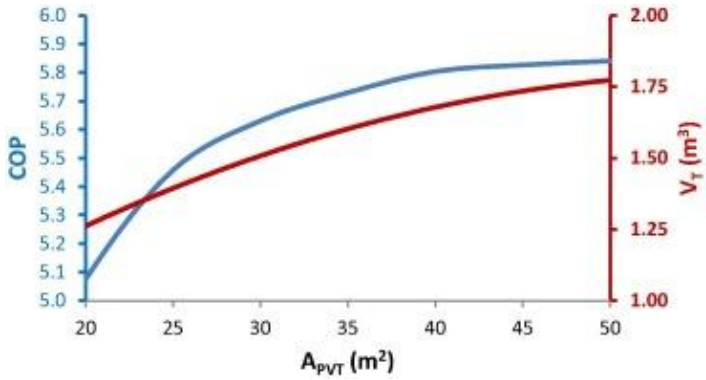


Figure 8. COP and storage tank volume for the examined PVT surfaces.(Bellos et al., 2016)

It was shown in the study that for both the simulation involving the flat plate collectors and that involving the photovoltaic panels, the COP of the water source heat pump increased as the collecting areas were increased, due to higher temperatures being involved, however it can be seen in Figure 7 and Figure 8 that in order to achieve the required temperatures within the building, around 20m^2 of collectors/panels were required.

2.5. Using Anthropogenic Exergy Thermal Sources with Heat Pump Systems

There is a lot of potential for using anthropogenic exergy sources, such as waste heat from industrial processes (European Heat Pump Association, 2015) or from fossil fuel driven systems within existing buildings, to improve the COP of heat pumps however there has not been a lot of study into this topic. These anthropogenic exergy sources, unlike natural exergy sources, could be considered to have an infinite thermal reservoir if they were run 100% of the time, however in real conditions these would most likely also be finite as the machinery would only run intermittently.

The method of using heat pumps to recover low grade waste heat and upgrade it to process heat in the industrial sector was considered by van der Bor et al. (2015) who analysed whether this was a better option than converting waste heat to electricity using a heat engine. It was determined that at waste inlet temperatures of 60°C or lower, heat pumps were 2.5-11 times more economically viable, but that heat engines become more viable at temperatures of 100°C or greater. While the study concludes that vapour compression heat pumps show a limited capability to upgrade waste heat streams, it does confirm that the COP decreases as the temperature difference between the waste outlets increases.

A study was carried out by Kim et al. (2013) who compared the performance of hybrid heat pumps to raise the temperature of waste heat compared to conventional boilers. It found that heat pumps provided much higher energy savings than boilers, however heat pumps were not able to reach the same temperature ranges as conventional boilers.

Some work has been done to study the effects of using waste heat to power absorption heat pumps (Wu et al., 2014) which is not directly relevant to this topic, however it does provide further evidence that low exergy sources of heat could be beneficial to the operation of heat pump systems. In the cases studied in the article, the use of waste heat in absorption heat pumps was particularly ideal in rural areas with little access to electricity.

Ommen et al. (2014) investigated the effect on the COP of a heat pump when integrated into a district heating scheme in a variety of different configurations. Within the study it discussed that by decentralising heat pumps within a larger district heating network, the pumps could utilise sources such as waste heat which has higher than ambient temperatures. Whilst not all configurations are relevant, two in which the heat pump utilises the return line from the district heating system as its source, are. When the results were analysed, the two aforementioned configurations had the highest COPs, with the highest overall COP being reached by the configuration which raised the return temperature for input into the CHP system as opposed to the configuration which raised the return temperature and supplied it to the output of the CHP system.

2.6. Identifying Low Exergy Thermal Sources in Buildings

It was defined earlier that an exergy source is one which can provide work to another system thereby improving the performance of that system. With that in mind, a low exergy source is one which is only capable of providing a low level of work to another system. Given that the work provided by an exergy source can be in the form of heat, a low exergy thermal source must therefore be a source which supplies a low level of heat to a system to improve its performance.

As there has been an abundance of investigations involving the use of natural low exergy thermal sources to improve the coefficient of performance of heat pumps, it was decided to focus on anthropogenic sources for further investigation. The anthropogenic low exergy thermal sources needed to improve the coefficient of performance of heat pumps must be available from the environment in which the heat pump is installed if any benefit is to be achieved with relative ease. Given that heat pumps are installed in building environments, the low exergy thermal sources must come from the anthropogenic systems at work within the building. There are many anthropogenic low exergy thermal sources within buildings, a list of which is contained on a Carbon Trust (2016) website discussing heat recovery from buildings. This list forms the first column in Table 1, below. Rather than being a complete list of all the individual variations which could occur, the list details the basic systems which could give off the waste heat.

Table 1. Anthropogenic low exergy thermal sources in buildings (Carbon Trust, 2016)

Source	Transience	Medium
Air compressors	Daily	Air
Boiler blowdown	Daily	Air
Boiler flue gases	Daily	Air
High temperature exhaust gas streams from furnaces, kilns, ovens and dryers	Daily	Air
Hot liquid effluents	Daily	Water
Power generation plant	Ad Hoc	Air
Process plant cooling systems.	Daily	Air/Water
Refrigeration plant	Constant	Air
Ventilation system extracts	Daily/Constant	Air

It can be seen from Table 1 that most of the anthropogenic low exergy sources available within a building take the form of exhaust air from existing systems within the building. This prevalence of heated air sources indicates that the most likely heat pumps to investigate are air source heat pumps, however it should be noted that water source heat pumps could also be used if the hot air was used to heat water in a storage tank.

2.7. Energy Savings from Building Upgrades

It has been stated that improving the COP of heat pumps is improving their efficiency, therefore it must be the case that there are energy savings involved when improving the COP. In order to accurately assess the potential of heat pumps with regards to energy savings, a comparison must be made against other energy saving measures such as building upgrades.

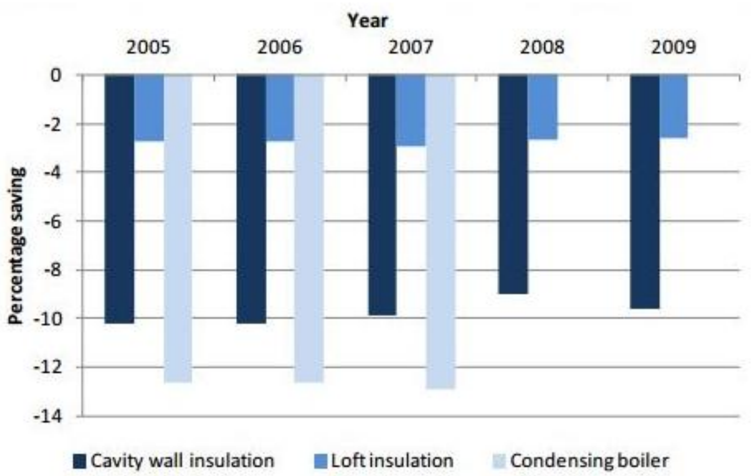


Figure 9. Summary of observed savings for energy efficiency measures (median) (Department of Energy & Climate Change, 2012)

It can be seen from Figure 9 that condensing boilers led to the highest energy savings, approximately 12% in 2005 through to 2007, however was no longer recorder thereafter. Cavity wall insulation led to the next highest savings, routinely achieving around 9% energy savings between 2005 and 2009. The measure which achieved the lowest percentage energy saving, approximately 2%, was loft insulation.

2.8. Conclusions

Based on the literature reviewed, it can be seen that there has been limited investigation into ways in which low exergy thermal sources could be utilised to increase the COP of a heat pump, however they have been focused on using natural exergy sources such as solar to improve water and geothermal source heat pumps. These studies highlighted that there is definite potential for low exergy sources to increase the COP of heat pumps, however they have not investigated in detail how effective anthropogenic exergy sources could be.

When identifying anthropogenic low exergy thermal sources, it was determined that most of these take the form of heated waste air, which lead to the conclusion that air source heat pumps should be concentrated on for future investigations within this report.

3. Heat Pump Sensitivity

3.1. Introduction

The strong dependency of COP to ΔT is widely advertised in scientific journals (Bellos et al., 2016, Cho, 2015) as well as on the websites of heat pump manufacturers and sellers (Kensa Heat Pumps, 2016, Industrial Heat Pumps, 2016). Also, based on Carnot theorem, it is accepted that the COP values of heat pumps are sensitive to temperature changes, be they source or sink temperature changes as earlier stated in Equation (2). However, through reviewing various makes and models of heat pumps it was noted that sensitivity to temperature difference can vary greatly, especially within particular temperature ranges.

When calculating the COP of a heat pump, manufacturers must conform to EN14511 standards to ensure that boundary conditions for testing are consistent across products, with these boundary conditions primarily relating to temperatures for different sinks and sources such as brine, water or air. In his article for REHVA, Klein (2012) stated that there are other factors which could affect the COP of a heat pump such as the occasional requirement to defrost the evaporator in colder conditions or the power consumption of any pumps and fans within the system. It is reasonable to assume that the heat pumps available on the market have different makes of pumps and fans, operating with different efficiencies and power requirements which may explain why heat pumps from different manufacturers have different trends when displayed graphically.

The aim of this section was to perform a comparison of multiple heat pumps and to analyse how they react to changes in source temperature. It was shown in Table 1 of this report that most low exergy thermal sources available from buildings take the form of waste air and as such it was decided to focus on air-to-air and air-to-water heat pumps. It could be argued that water source heat pumps could also be included in the comparison as there are many benefits to using them, such as sustaining an increased COP through storing waste heat in a storage tank. Whilst they could lead to prolonged increased COP compared to air source heat pumps being fed from the same low exergy thermal source, studies such as Kuang and Wang (2003) and Bellos et al. (2016) have already sufficiently discussed the sensitivity of water source heat pumps to temperature changes.

3.2. Materials and Methods

3.2.1. Heat Pump Technical Data

In Table 2, below, the heat pumps being used for the comparison are listed, detailing the manufacturer, series, model combination, nominal heating capacities and nominal power inputs. It should be noted that these particular models were chosen because an appropriate amount of technical data was available for each, including heating capacity information with at least four different temperature data points. Additional information for each heat pump, including the number of data points and the specific sink and source temperatures used, is included in Appendix A – Daikin Heat Pump Data through to Appendix E – Toshiba Heat Pump Data.

The majority of selected heat pumps were air-to-air heat pumps however air-to-water heat pumps were also selected in order to observe whether they reacted differently to air-to-air heat pumps. Additionally, heat pumps of varying heating capacities and power inputs were selected to determine if the size of the unit had any effect on its sensitivity to changes in source temperature.

Table 2. Heat pump ID tags and specifications.

ID tag	Manufacturer	Series	Model Combination	Nominal Heating Capacity (kW)	Nominal Power Input - Heating (kW)	Source
D1	Daikin	VRV III	RXYQ5P9W1B + RXYQ-5P9	16	4	(Daikin, 2011)
D2	Daikin	VRV III	RXYQ5P9W1B + RXYQ-8P9	25	5.56	(Daikin, 2011)
D3	Daikin	VRV III	RXYQ5P9W1B + RXYQ-10P9	31.5	7.7	(Daikin, 2011)
D4	Daikin	VRV III	RXYQ5P9W1B + RXYQ-12P9	37.5	9.44	(Daikin, 2011)
D5	Daikin	VRV III	RXYQ5P9W1B + RXYQ-14P9	45	11.3	(Daikin, 2011)
D6	Daikin	VRV III	RXYQ5P9W1B + RXYQ-16P9	50	12.9	(Daikin, 2011)
D7	Daikin	VRV III	RXYQ5P9W1B + RXYQ-18P9	56.5	15.3	(Daikin, 2011)
K1	Kingspan	Aeromax Plus	4kW	4.1	1.01	(Kingspan, 2011)
K2	Kingspan	Aeromax Plus	6kW	5.8	1.37	(Kingspan, 2011)
K3	Kingspan	Aeromax Plus	8kW	7.2	1.82	(Kingspan, 2011)
K4	Kingspan	Aeromax Plus	12kW	11.9	3.01	(Kingspan, 2011)
K5	Kingspan	Aeromax Plus	15kW	14.5	3.57	(Kingspan, 2011)
S1	Samsung	Slim 1 Way Cassette	AC026FCADEH/EU + AC026FB1DEH/EU	4.6	1.3	(Samsung, 2015)
S2	Samsung	Slim 1 Way Cassette	AC035FCADEH/EU + AC035FB1DEH/EU	4.75	1.39	(Samsung, 2015)
S3	Samsung	Mini 4 Way Cassette	AC026FCADEH/EU + AC026FBNDEH/EU	4.6	1.4	(Samsung, 2015)
S4	Samsung	Mini 4 Way Cassette	AC035FCADEH/EU + AC035FBNDEH/EU	5	1.4	(Samsung, 2015)
S5	Samsung	Mini 4 Way Cassette	AC052FCADEH/EU + AC052FBNDEH/EU	7.5	2.4	(Samsung, 2015)
S6	Samsung	Mini 4 Way Cassette	AC060FCADEH/EU + AC060FBNDEH/EU	9	3.6	(Samsung, 2015)
S7	Samsung	Mini 4 Way Cassette	AC071FCADEH/EU + AC071FBNDEH/EU	10	3.8	(Samsung, 2015)
T1	Toshiba	Estia	HWS-803H-E + HWS-803XWH**-E	8	1.82	(Toshiba, 2010b)
T2	Toshiba	Estia	HWS-1103H-E + HWS-1403XWH**-E	11.2	2.35	(Toshiba, 2010b)
T3	Toshiba	Estia	HWS-1403H-E + HWS-1403XWH**-E	14	3.11	(Toshiba, 2010b)
WB1	Worcester Bosch	Greensource	7-716-150-179	4	1.3	(Worcester Bosch Group, 2013)

3.2.2. Heat Pump COP vs Source Temperature

In order to properly compare the sensitivity of heat pumps, samples of air source heat pumps were selected from a number of brands and figures were taken from heating capacity tables within their respective data sheets. An example of one of these tables is shown below in Table 3.

Table 3. Sample Heating Capacity Table

ID Tag	Sink Temperature (°C)	Source Temperature (°C)	Heating Capacity (kW)	Power Input (kW)
S1	20	-15	2.31	1.10
S1	20	-10	2.72	1.07
S1	20	7	3.30	0.91
S1	20	24	3.52	0.96

The source temperature values shown in the sample table shown above, and the respective tables for the other heat pumps, were outdoor air temperature values. For each source temperature, the heating capacity and power input values were used with Equation (1) in order to calculate COP values which could be used to create COP vs Source Temperature profiles. The full tables containing the technical data and calculated COP values for each heat pump are included in the appendices Appendix A – Daikin Heat Pump Data through to Appendix E – Toshiba Heat Pump Data.

Due to the different amount of source temperature data points across the manufacturers, the initial graphical comparison of the COP vs Source Temperature profiles consisted of discontinuous plots which made it difficult to perform an accurate comparison. To rectify this, each manufacturer's data was extrapolated to ensure the profiles passed through all temperature data points between their first and last points, thus resulting in unbroken graphical profiles. The tables containing the extrapolated data are included in Appendix F – Extrapolated Heat Pump Data.

3.2.3. Overall Sensitivity: Air-to-Air vs Air-to-Water

The variable nature of the COP vs Source Temperature profile, particularly the instances where the COP decreased instead of increasing, meant that the results required further analysis. The rate of change of the COP (ΔCOP) per the change in source temperature (ΔT_S), $\Delta COP/\Delta T_S$ provided a clear way of analysing the sensitivity of the heat pump, therefore it was used to determine the overall sensitivity of each of the heat pumps.

3.2.4. Sensitivity per Temperature Range

It was clear that the overall sensitivity analysis of the heat pumps was not sufficiently in-depth therefore further analyses were performed using the same method, but grouping the source temperatures as either low, medium or high temperature ranges. By looking at each range distinctly the rate of COP increase for each heat pump could be determined and could be used to determine if there were any particular temperature ranges in which the heat pumps were more sensitive. At this stage each heat pump was compared directly, with no distinction made between air-to-air and air-to-water heat pumps.

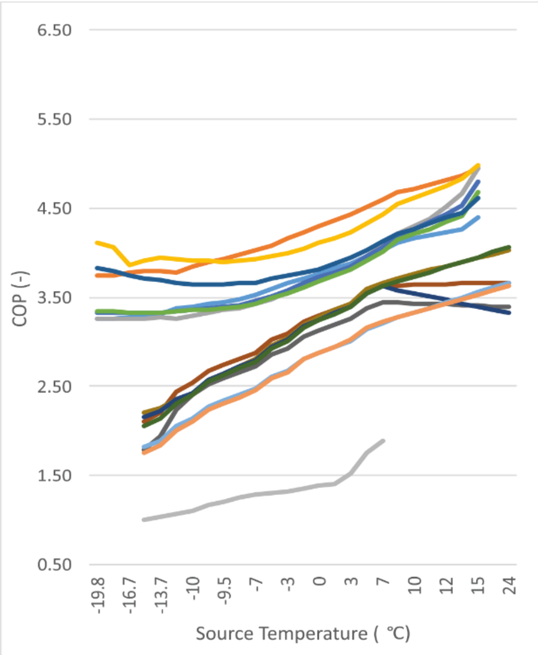
3.2.5. Low Capacity vs High Capacity

After comparing sensitivity of the heat pumps across various temperature ranges and heat pump types, it was decided to determine whether the sensitivity of the heat pumps was determined by the nominal heating capacity of the heat pumps. To do this, the nominal heating capacities were divided into two ranges; “low” encompassing nominal heating capacities up to 10kW and “high” encompassing nominal heating capacities from 11kW upwards.

3.3. Results

3.3.1. Heat Pump COP vs Source Temperature

In the two graphs below, Figure 10 and Figure 11 the lines represent the COP of each heat pump as the source temperature increases. It should be noted that Figure 10 pertains to air-to-air source heat pumps, designated D, S and WB, with sink temperature of 20°C whilst Figure 11 pertains to air-to-water source heat pumps designated K and T with sink temperature of 35°C.



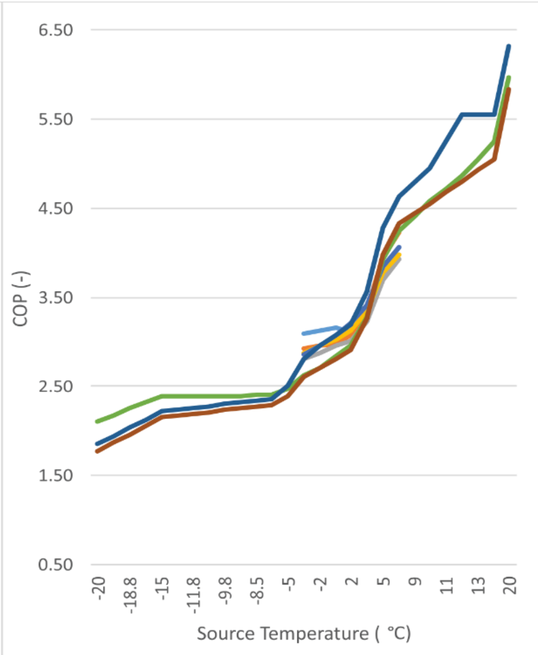


Figure 10. Air-to-air heat pumps: COP vs source temperature

Figure 11. Air-to-water heat pumps: COP vs source temperature

It can be seen from Figure 10 that there was a lot of variation between the heat pumps, which whilst indicating that overall all COPs increase as the source temperature is increased, also shows that even amongst manufacturers there is no uniformity. There are also instances on the graph above which show the COP decreasing as the source temperature is increasing which seems to be in direct contradiction to Carnot Theorem. It should be noted that for heat pumps designated certain heat pumps, the COP reduction between 20°C and 24°C was due to the source temperature exceeding the sink temperature therefore this was not considered to be a potential issue.

Contrary to Figure 10, the heat pumps included in Figure 11 followed similar trends to one another albeit with minor differences in magnitude. The major difference between the heat pumps was the range of source temperature across which COP data was available, with some heat pumps covering a much smaller range than the rest. It was determined that heat pump T2 had the most obvious variation to the other heat pumps in the source temperature range between 5°C and 15°C.

As the y-axis of the two graphs were the same, it could be seen that the air-to-water heat pumps had a steeper profile than those of the air-to-air heat pumps which indicated that overall they appear to have a greater sensitivity to source temperature change.

3.3.2. Overall Sensitivity: Air-to-Air vs Air-to-Water

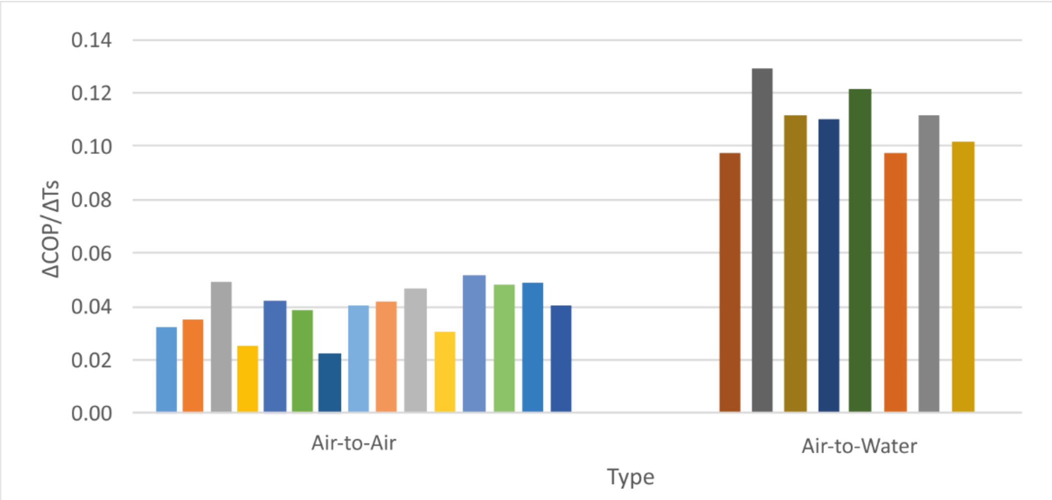


Figure 12. Overall sensitivity: air-to-air vs air-to-water

It can be seen in Figure 12 that there is a vast difference in sensitivity between the air-to-air and air-to-water heat pumps, which confirms that which had been previously indicated in Figure 10 and Figure 11. The air-to-water source heat pumps were seen to be approximately twice as sensitive as the selected air-to-air heat pumps.

Overall the heat pump with the highest sensitivity was K2 of which the COP increased by 0.13 every degree whilst the heat pump with the lowest sensitivity was D7 which only increased by 0.02 every degree indicating that K2 is 6.5 times more sensitive than D7.

3.3.3. Sensitivity per Temperature Range

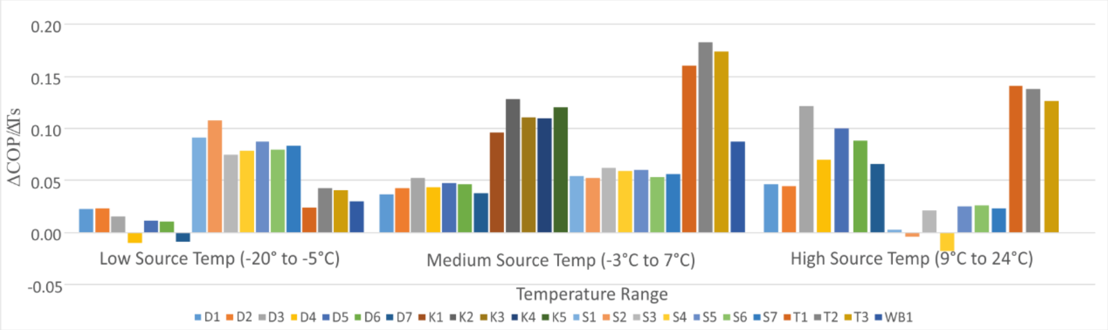


Figure 13. Sensitivity per temperature range

When split into temperature ranges, it can be seen that the sensitivity of heat pumps is more complex than when viewed overall. In the low temperature range, which encompasses temperatures from -20°C to -5°C, heat pumps D4 and D7 both decrease by -0.01 per degree. The other heat pumps designated D had a lower COP increase rate in the low temperature range compared to the medium temperature range where they approximately doubled. The rate dropped again in the high temperature range where heat pumps S2 and S4 became negative. Conversely it can be seen that the rate at which the COP of heat pumps S1 to S7 increased was greater in the low temperature range than it was in the medium temperature range. The COP increase rates were even lower when those heat pumps moved into the high temperature range.

The heat pumps designated T followed a similar path to heat pumps designated S. Within the medium temperature range, heat pump T2 reached the greatest sensitivity with the COP increasing by 0.18 for every degree of increase in source temperature. The K type heat pumps were limited to the medium temperature range therefore no comparison with the low and high ranges could be performed. The biggest difference between the temperature ranges was that of the WB type heat pump whose sensitivity tripled in the medium range compared to the low temperature range.

3.3.4. Low Capacity vs High Capacity

It can clearly be seen from Figure 14 that the sensitivity of the heat pumps was not directly related to the nominal heating capacity range to which they were designed. It can be seen that many of the least sensitive heat pumps are within the high nominal heating capacity range whilst the most sensitive heat pumps are contained both within the low and high nominal heating capacity ranges.

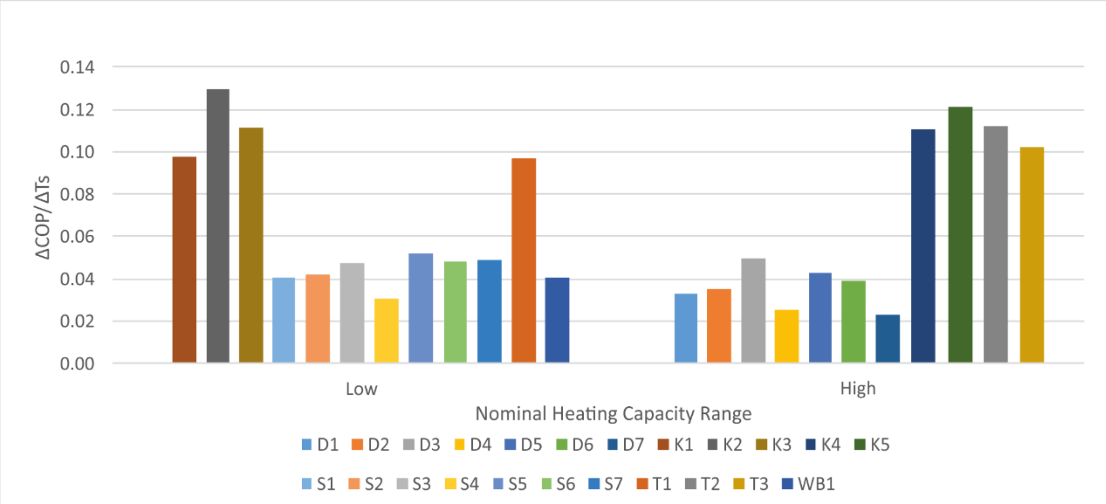


Figure 14. Overall heat pump sensitivity per nominal heating capacity

3.4. Conclusion

Within this section of the report it was intended to investigate the sensitivity of heat pumps by evaluating the rate at which the COP of the heat pumps altered as the source temperature was increased. It was discovered, from the sources available, that air-to-water heat pumps tend to be more sensitive than air-to-air heat pumps, being almost twice as sensitive in most circumstances. It was also determined that the nominal heating capacity, which the heat pump was designed to meet, has no direct effect on the sensitivity of the heat pump to source temperature change.

One of the most prominent discoveries of the analysis was that there were instances where the COP of a heat pump would decrease as the source temperature was increased, typically occurring at very low source temperatures. Further investigation should be undertaken in future to determine the root cause of this decrease in COP, whether it be that the efficiencies of individual parts within the heat pump system drive down the COP or whether it be dependent on the type of refrigerant fluid used within the system.

Based on the analysis performed above it was determined that overall the heat pump with the highest sensitivity was K2, however this particular heat pump only had data over a small range of source temperatures, as did the other heat pumps designated K which achieved high sensitivity. Looking at the highest sensitivity out of the other heat pumps, it was determined that T2 had a sufficiently high sensitivity over a large range of source temperatures. When reviewing the temperature ranges, it was discovered that T2 reached the highest overall sensitivity of all the heat pumps when in the medium temperature range, maintaining a high sensitivity in the high temperature range, however in the low temperature range the sensitivity of the heat pump is only around a quarter of that experienced in the medium temperature range.

4. Using Low Exergy Sources with a Heat Pump

4.1. Introduction

There are many ways in which low exergy sources could be incorporated into a heat pump system, therefore it is important to gain an understanding of the potential impacts these different schemes could lead to. In order to gain an understanding of many of these potential effects, four schemes were selected and are individually detailed below.

From the analysis of the schemes, it was hoped to determine whether there were improvements to the COP of the heat pump through incorporating the low exergy sources, and also to determine whether one particular scheme stood out as being the most advantageous.

4.2. Materials and Methods

4.2.1. General Methodology

In the previous section heat pump T2 was determined to be the most sensitive of the heat pumps which covered a large range of source temperatures, therefore it was selected as the heat pump for use within this section of the report. Based on the COP data from its technical data sheet, shown below in Table 4, a graph, Figure 15, was created indicating the equation of the line for COP vs Source Temperature which could be used in future calculations.

Table 4. Heat pump T2 COP data

ID Tag	Sink Temperature (°C)	Source Temperature (°C)	Temperature Difference (ΔT) (°C)	Heating Capacity (kW)	Power Input (kW)	COP	Carnot COP
T2	35	-20	55	5.48	2.97	1.85	5.60
T2	35	-15	50	6.86	3.09	2.22	6.16
T2	35	-7	42	8	3.4	2.35	7.33
T2	35	-2	37	9.9	3.35	2.96	8.32
T2	35	2	33	10.55	3.3	3.20	9.33
T2	35	7	28	14.97	3.23	4.63	11.00
T2	35	10	25	15.87	3.21	4.94	12.32
T2	35	12	23	16.62	3	5.54	13.39
T2	35	15	20	17.7	3.19	5.55	15.40
T2	35	20	15	20.01	3.17	6.31	20.53

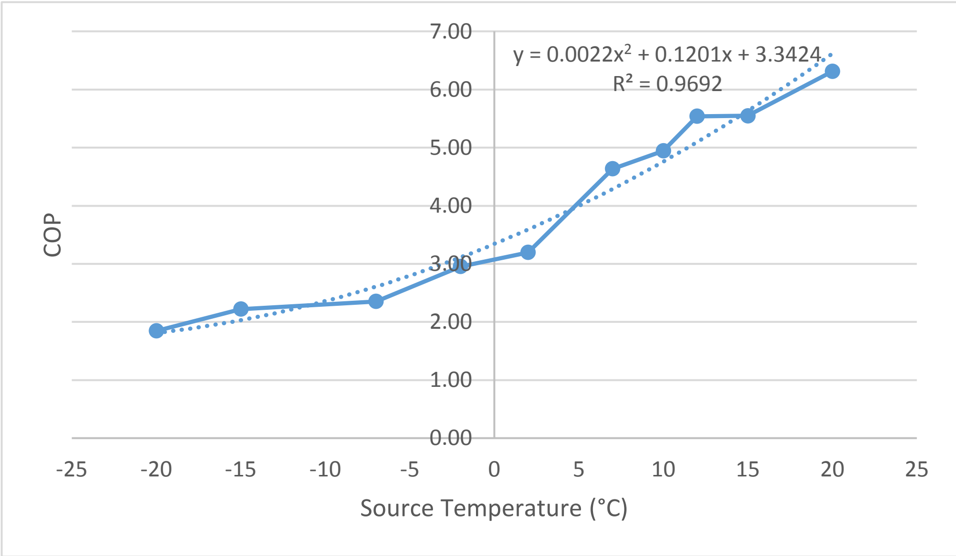


Figure 15. Heat pump T2: COP vs Source Temperature line equation

The equation for the relationship between COP and source temperature (°C) is shown below in Equation (3), which according to the R^2 number of 0.9692 is approximately 97% accurate based on the source data.

$$COP = 0.0022T_{source}{}^2 + 0.1201T_{source} + 3.3424 \quad (3)$$

To prove the accuracy of the line equation given, it was used to determine the percentage difference between the actual COP and the calculated COP when using the known source temperature figures.

Table 5. COP line equation validation

Source Temperature (°C)	COP	Calculated COP	Difference	% Difference
-20	1.85	1.82	0.02	1.34%
-15	2.22	2.04	0.18	8.30%
-7	2.35	2.61	-0.26	-10.90%
-2	2.96	3.11	-0.16	-5.27%
2	3.20	3.59	-0.39	-12.34%
7	4.63	4.29	0.34	7.42%
10	4.94	4.76	0.18	3.65%
12	5.54	5.10	0.44	7.94%
15	5.55	5.64	-0.09	-1.63%
20	6.31	6.62	-0.31	-4.94%

It can be seen from table that the largest percentage difference between the actual COP and calculated COP was 12.34% occurring when the source temperature was 2°C. The percentage differences vary due to the fact that a second order polynomial equation was used which is more linear than the actual trend of the COP to Source Temperature line, which was also the reason that some differences were positive whilst others were negative. To reduce the percentage difference between the COP values, a higher order polynomial equation could have been used, however it was decided that for the purposes of this report, the percentage difference values were acceptable.

Given that it was an air to water heat pump which was selected, it was convenient to consider the system to be supplying an underfloor heating network, which CIBSE (2010) indicated should operate with a low temperature range, between 35°C and 40°C. As the technical data for the chosen heat pump referenced a water outlet temperature of 35°C, it was decided to use this value in future calculations. It was also assumed that the heat pump was maintaining an indoor air temperature, $T_{I,}$ of 20°C. The source temperature described in the technical data sheet was renamed as the outdoor temperature, T_O, to avoid confusion because the calculations described from here onwards calculate new source temperatures. The schematics shown in the sub-sections below are simplistic theoretical representations of the heat pump system and therefore do not show the condenser submerged in a water tank feeding the pipe network attributed to an underfloor heating network.

The building air flow rate used for the calculations was 8 litres per second per person (Clark, 2013). For use in the calculation the litres per second figures was converted to cubic metres per second, with an assumption made that the room contained twenty people. The flow rate of the fan in the evaporator unit was stated as 101m^3/h which converted to 1.68m^3/s (Toshiba, 2010b). It should be noted that Equations (5),(6),(7) and (8) are only accurate if the air flow rate from the building is lower than the air flow rate of the fan within the evaporator.

The compressor used within the selected heat pump is the Toshiba DA422A3F-25M which is a twin rotary type with DC-inverter variable speed control (Toshiba, 2010a). An accurate efficiency was unable to be attained from any technical data sheet, therefore an estimated efficiency of 75% was used, based on information gained in an online article (Campbell, 2011). The heat recovery unit used for the calculations was the Toshiba VN-M350HE which was up to 83% efficient according to its technical data sheet (Toshiba, 2013). The above-mentioned figures are all shown in Table 6, below.

Table 6. Common values for all calculations.

Category	Value	Unit	Symbol
Air Density	1.2	kg/m^3	ρ_{Air}
Air Specific Heat	1000	J/kg°C	C_{Air}
Heat Pump Nominal Power	2350	W	
Indoor Temperature	20	°C	T_I
Water Outlet Temperature	35	°C	
Heat Recovery Efficiency	0.83		HR_{Eff}
Air Flow Rate – Evaporator Fan	1.68	m3/s	Q_E
Air Flow Rate - Building	0.16	m3/s	Q_B
Waste Energy - Compressor	590	W	E_C

Once the new source temperatures were calculated using Equations (5), (6), (7) and (8), the new COP figures were calculated using Equation (3).

In order to equate a COP increase to an energy saving, it had to be understood that the heat output, Q_{Output}, of the heat pump would remain the same when the COP increased, meaning that the work input, W would be reduced. Given that Q is constant, Equation (1) could be altered as follows:

$$COP_1 \times W_1 = COP_2 \times W_2 \tag{4}$$

Once the new coefficient of performance, COP_2, is calculated, both W_1 and W_2 can could be calculated, enabling the percentage difference between the work input values to be calculated. This difference in work input values equates to the energy saving resulting from the increase in COP.

4.2.2. Using Indoor Air to Alter Source Temperature

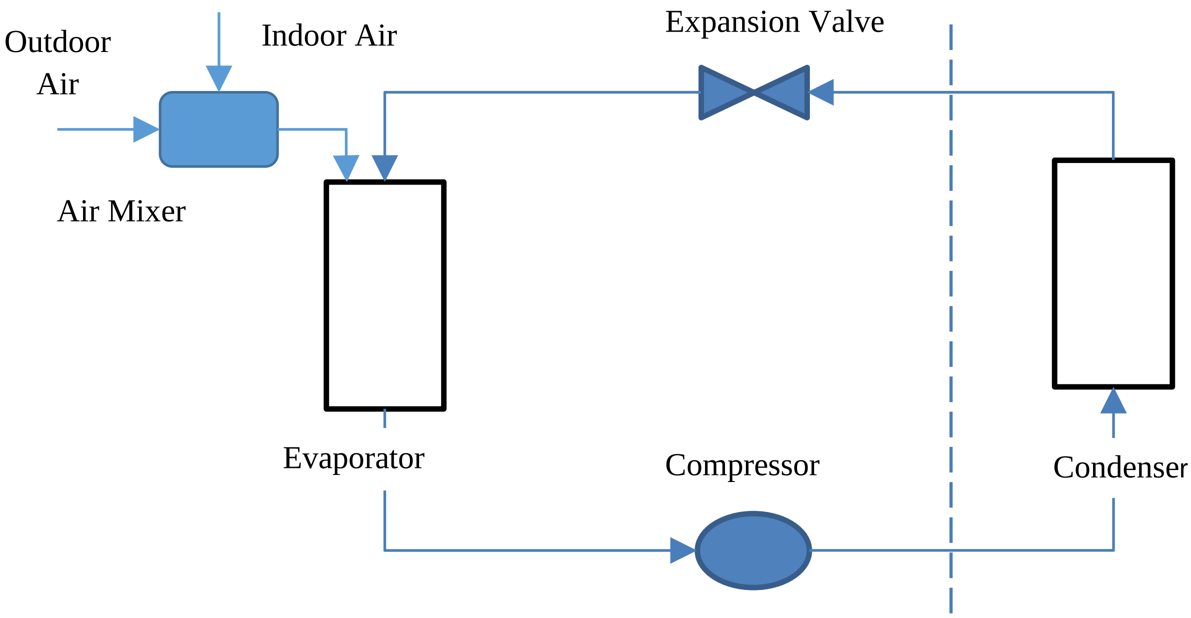


Figure 16. Using indoor air to alter temperature of outdoor air supply

The schematic shown in Figure 16 is a theoretical configuration which indicates that the air source heat pump was fed by a mixture of outdoor air and indoor air directly vented into the air mixer. The indoor air should cause the temperature of the outdoor air within the air mixer to increase before being supplied to the evaporator unit.

Theoretically, upon start-up of the heat pump, the indoor temperature would be low and increase as the heating system stabilises the temperature within the room. For the purposes of these calculations it was assumed that the room had already reached temperature. These assumptions isolated the effect which the outdoor temperature has on the COP.

The impact of the indoor air on the outdoor air supply had to be taken into account, which resulted in Equation (5), shown below:

$$T_{source} = \frac{(T_O \times (Q_E - Q_B) + T_I \times Q_B)}{Q_E} \qquad (5)$$

4.2.3. Using Indoor Air with Heat Recovery to Alter Source Temperature

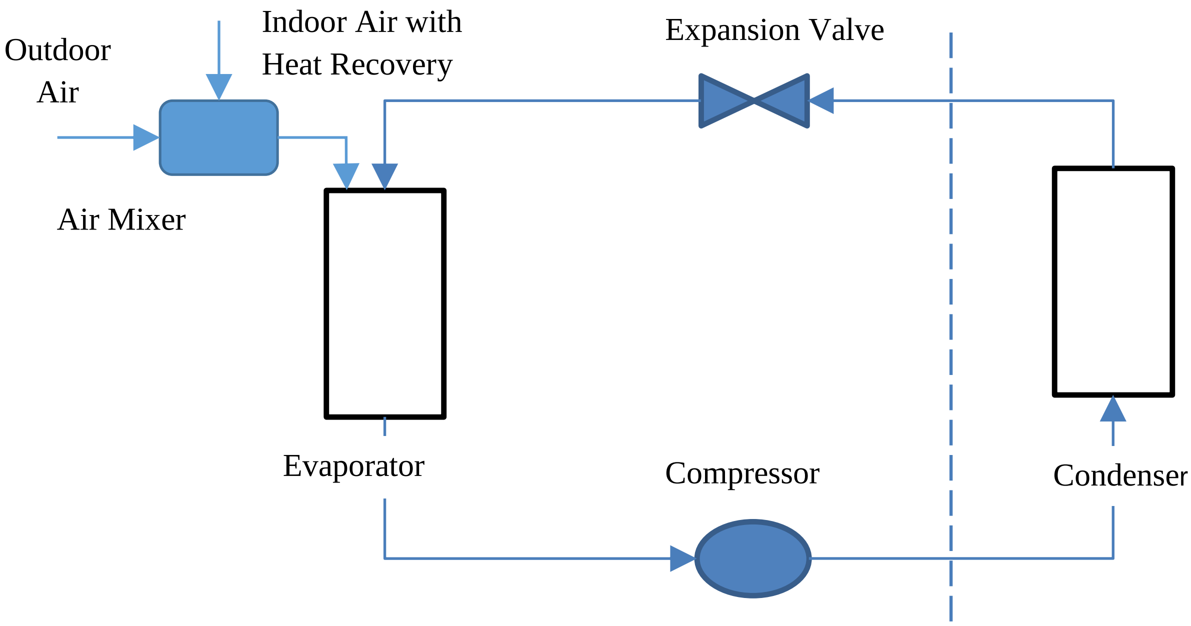


Figure 17. Using indoor air and heat recovery to alter temperature of outdoor air supply

As before, the schematic shown in Figure 17 is a theoretical configuration, this time showing that the air source heat pump was again fed by both the outdoor and indoor air, however the indoor air was provided through a heat recovery system. Once again, for the purposes of these calculations it was assumed that the room had already reached temperature in order to isolate the effect which the outdoor temperature has on the COP.

The impact of the indoor air vented via the heat recovery system on the outdoor air supply had to be taken into account which resulted in Equation (6), shown below:

$$T_{source} = \frac{(T_O \times (Q_E - Q_B) + ((T_I - T_O) \times HR_{Eff} + T_O) \times Q_B)}{Q_E} \quad (6)$$

4.2.4. Using Indoor Air and Waste Heat from Compressor to Alter Source Temperature

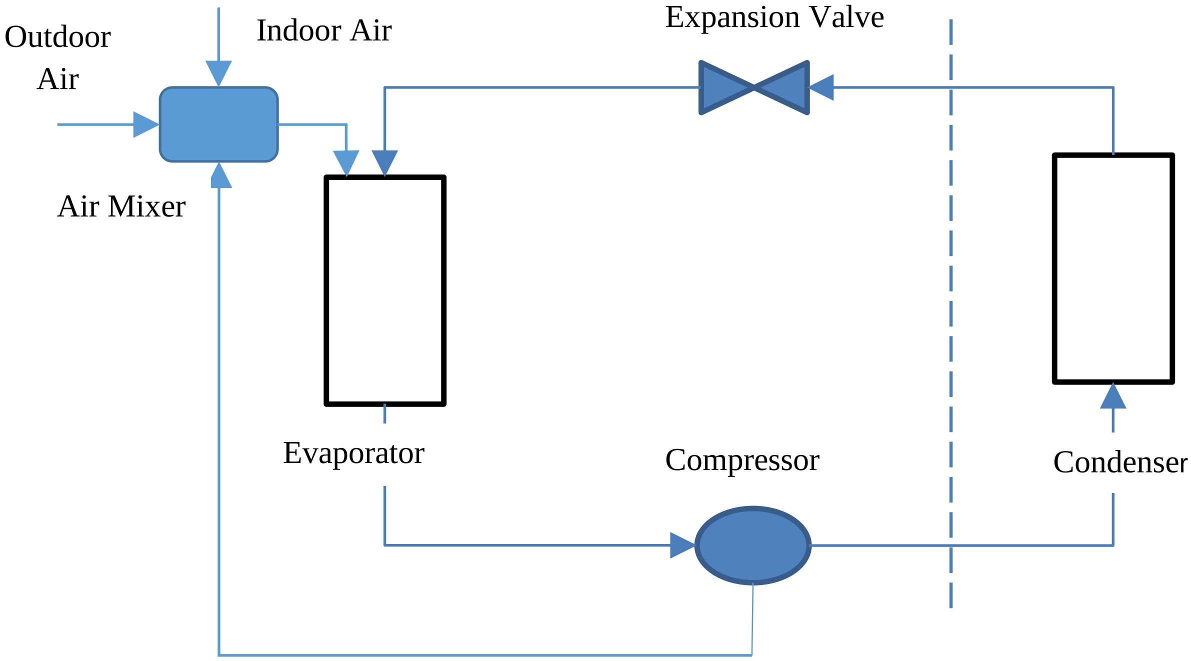


Figure 18. Using indoor air and waste heat from compressor to alter temperature of outdoor air supply

In Figure 18, the schematic shows a theoretical configuration of an air source heat pump being fed by three sources; outdoor air, directly vented indoor air and waste heat from the compressor. The waste heat from the compressor and the indoor air should both cause the temperature of the outdoor air within the air mixer to increase before being supplied to the evaporator unit.

Theoretically, upon start-up of the heat pump, the COP of the heat pump should be low, before increasing as heat is generated in the compressor unit, whilst at the same time the indoor temperature would start low and increase as the heating system stabilised the temperature within the room. For the purposes of these calculations it was assumed that the room had already reached temperature and the compressor was already up to temperature. These assumptions isolated the effect which the outdoor temperature has on the COP.

The impact of the indoor air and the waste heat from the compressor on the outdoor air supply had to be taken into account which resulted in Equation (7), shown below:

$$T_{source} = \frac{(T_O \times (Q_E - Q_B) + T_I \times Q_B)}{Q_E} + \frac{E_C}{(Q_E \times \rho_{Air} \times C_{Air})} \quad (7)$$

4.2.5. Using Indoor Air with Heat Recovery and Waste Heat from Compressor to Alter Source Temperature

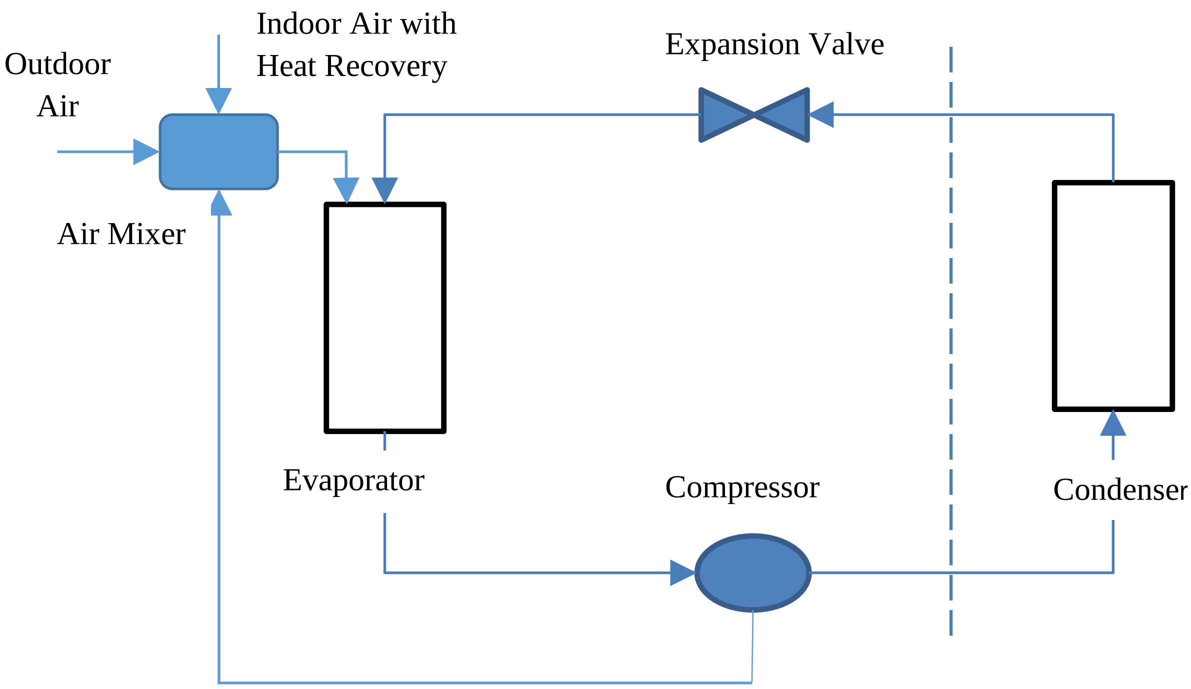


Figure 19. Using indoor air with heat recovery and waste heat from compressor to alter temperature of outdoor air supply

In Figure 19, the schematic shows a theoretical configuration in which it can be seen that the air source heat pump was fed by outdoor air, waste heat from the compressor and indoor air from a heat recovery system. Once again, for the purposes of these calculations it was assumed that both the room and compressor had already reached temperature in order to isolate the effect which the outdoor temperature has on the COP.

In order to determine the source temperature entering the evaporator unit, a new calculation had to be performed which took into account the impact of the indoor air with heat recover and waste heat from the compressor on the outdoor air supply. The equation used for this is shown in Equation (8), shown below:

$$T_{source} = \frac{(T_O \times (Q_E - Q_B) + ((T_I - T_O) \times HR_{Eff} + T_O) \times Q_B)}{Q_E} + \frac{E_C}{(Q_E \times \rho_{Air} \times C_{Air})} \quad (8)$$

4.3. Results

4.3.1. Using Indoor Air to Alter Source Temperature

Table 7. Using indoor air to alter source temperature: results

Outdoor Temperature (°C)	COP	Source Temperature (°C)	New COP	COP Increase	Energy Consumption
-20	1.85	-16.19	1.97	7%	-7%
-15	2.22	-11.67	2.24	1%	-1%
-7	2.35	-4.43	2.85	21%	-18%
-2	2.96	0.10	3.35	13%	-12%
2	3.20	3.71	3.82	19%	-16%
7	4.63	8.24	4.48	-3%	3%
10	4.94	10.95	4.92	0%	0%
12	5.54	12.76	5.23	-6%	6%
15	5.55	15.48	5.73	3%	-3%
20	6.31	20.00	6.62	5%	-5%

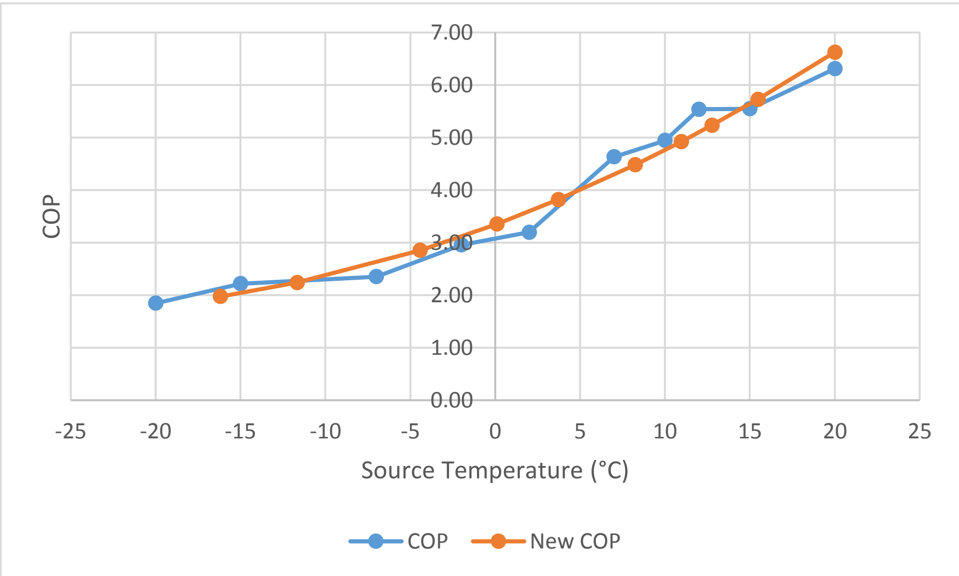


Figure 20. Using indoor air to alter outdoor air temperature: graph

It can be seen from Table 7 and Figure 20 that directly venting the indoor air raise the temperature of the outdoor air in the air mixer results in increases in COP at most outdoor temperatures. The greatest increase in COP occurs at -7°C where a 21% increase is achieved, which results in an approximate energy saving of 18%. Similarly, high increases in COP are achieved between -2°C and 2°C, which also see significant energy savings. There are some anomalies in the results at 7°C and 12°C, showing a reduction in COP and therefore an increase in energy consumption. A sample calculation is shown in full in Appendix H – Sample Heat Pump COP Calculations

4.3.2. Using Indoor Air with Heat Recovery to Alter Source Temperature

Table 8. Using indoor air with heat recovery to alter source temperature: results

Outdoor Temperature (°C)	COP	Source Temperature (°C)	New COP	COP Increase	Energy Consumption
-20	1.85	-16.84	1.94	5%	-5%
-15	2.22	-12.23	2.20	-1%	1%
-7	2.35	-4.87	2.81	19%	-16%
-2	2.96	-0.26	3.31	12%	-11%
2	3.20	3.42	3.78	18%	-15%
7	4.63	8.03	4.45	-4%	4%
10	4.94	10.79	4.89	-1%	1%
12	5.54	12.63	5.21	-6%	6%
15	5.55	15.40	5.71	3%	-3%
20	6.31	20.00	6.62	5%	-5%

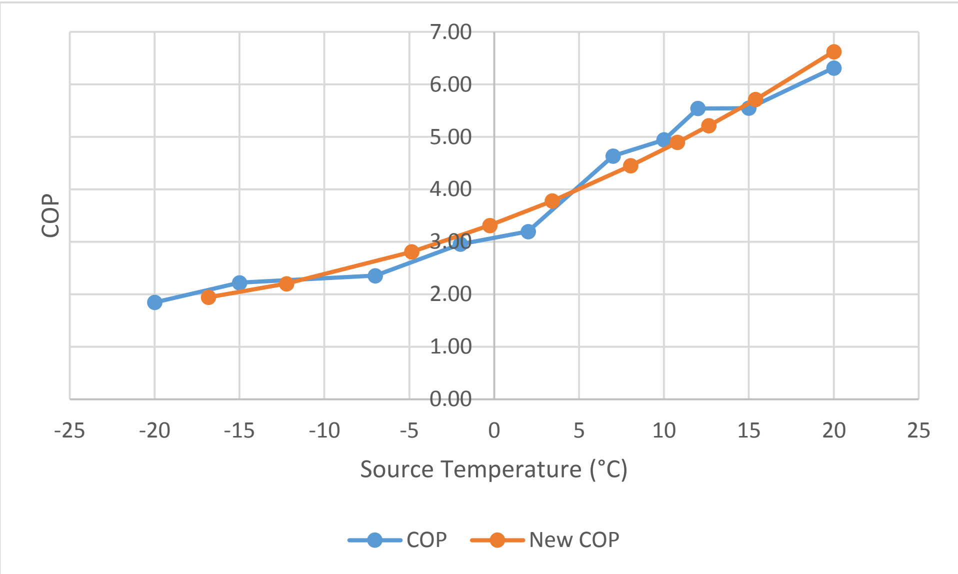


Figure 21. Using indoor air with heat recovery to alter source temperature: graph

Table 8 and Figure 21 show that whilst there are still increases in COP in most cases, they are not as significant as those shown in Table 7. Where previously the increase in COP at -7°C had been 21%, in this instance it was down to 19%, likewise the increases at -2°C and 2°C were reduced to 12% and 18% respectively. Additionally, the instances where the COP decreased increased to four where there had only been two in Table 7. The maximum energy saving in the heat pump, achieved through using heat recovery system to supply the indoor air was 16% which may be offset slightly be the energy required to operate the heat recovery system itself. A sample calculation is shown in full in Appendix H – Sample Heat Pump COP Calculations

4.3.3. Using Indoor Air with Waste Heat from Compressor to Alter Source Temperature

Table 9. Using indoor air with waste heat from compressor to alter source temperature: results

Outdoor Temperature (°C)	COP	Source Temperature (°C)	New COP	COP Increase	Energy Consumption
-20	1.85	-15.90	1.99	8%	-7%
-15	2.22	-11.37	2.26	2%	-2%
-7	2.35	-4.14	2.88	23%	-18%
-2	2.96	0.39	3.39	15%	-13%
2	3.20	4.01	3.86	21%	-17%
7	4.63	8.53	4.53	-2%	2%
10	4.94	11.25	4.97	1%	-1%
12	5.54	13.05	5.29	-5%	5%
15	5.55	15.77	5.78	4%	-4%
20	6.31	20.29	6.69	6%	-6%

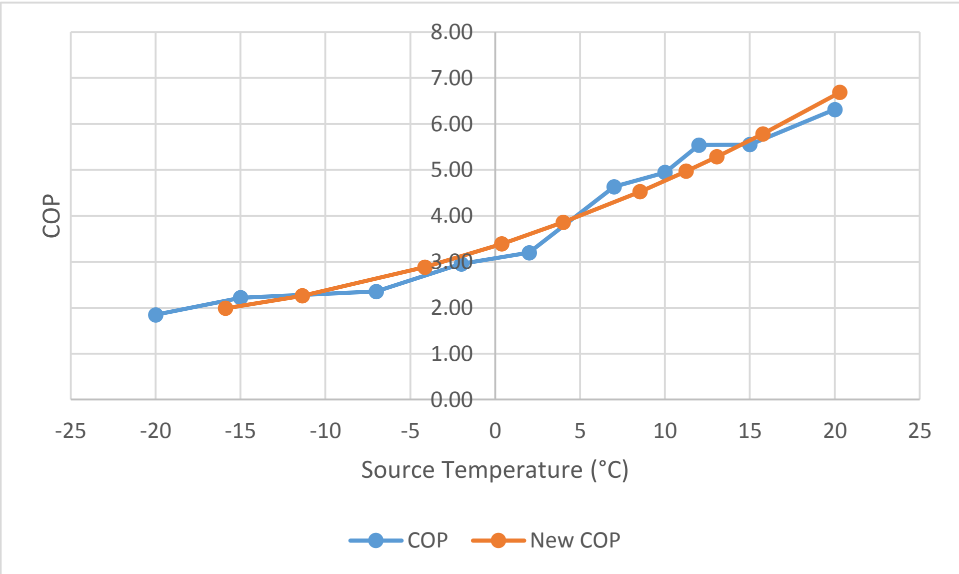


Figure 22. Using indoor air with waste heat from compressor to alter source temperature:

It can be seen in Table 9 and Figure 22, above, that using waste heat from the compressor along with the directly vented indoor air causes the COP to increase more than when only the directly vented indoor air is used. The largest COP increase, once again at an outdoor temperature of -7°C, was 23% which was 2% greater than when only the directly vented air was used as a low exergy thermal source. This 23% COP increase still resulted in an 18% saving in energy which had been the maximum in Table 7. Further COP increase worth noting were 15% at -2°C and 21% at 2°C. A sample calculation is shown in full in Appendix H – Sample Heat Pump COP Calculations

4.3.4. Using Indoor Air with Heat Recovery and Waste Heat from Compressor to Alter Source Temperature

Table 10. Using indoor air with heat recovery and waste heat from compressor to alter source temperature: results

Outdoor Temperature (°C)	COP	Source Temperature (°C)	New COP	COP Increase	Energy Consumption
-20	1.85	-16.55	1.96	6%	-6%
-15	2.22	-11.94	2.22	0%	0%
-7	2.35	-4.57	2.84	21%	-17%
-2	2.96	0.03	3.35	13%	-12%
2	3.20	3.72	3.82	19%	-16%
7	4.63	8.32	4.49	-3%	3%
10	4.94	11.08	4.94	0%	0%
12	5.54	12.93	5.26	-5%	5%
15	5.55	15.69	5.77	4%	-4%
20	6.31	20.29	6.69	6%	-6%

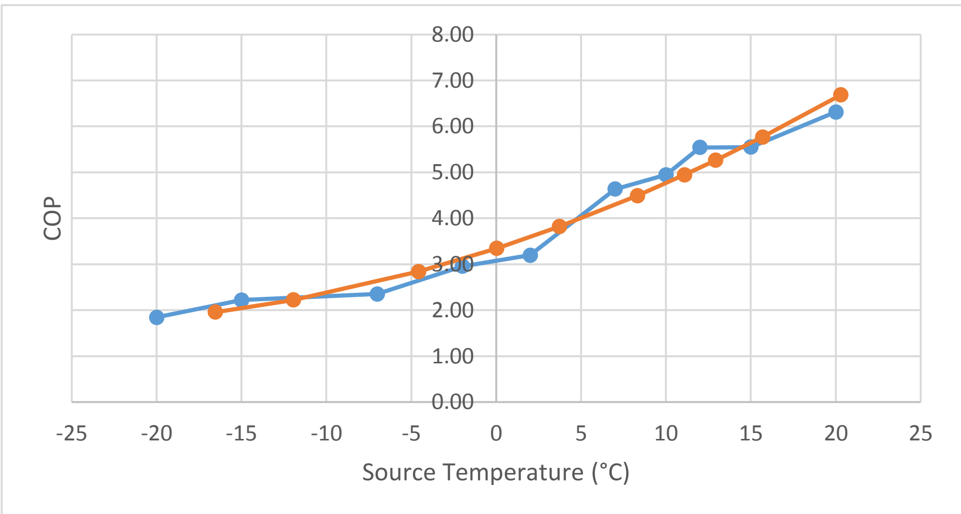


Figure 23. Using indoor air with heat recovery and waste heat from compressor to alter source temperature: results

Table 10 and Figure 23 indicate that once again the waste heat from the compressor does improve the COP of the heat pump more than simply using the indoor air provided through the heat recovery system. It appears from the COP increases achieved that by coupling the waste heat from the compressor with indoor air provided by a heat recovery system, the waste heat from the compressor acts to negate the heat lost through the inefficiency of the heat recovery system. The maximum COP increase is 21% followed by 13% and 19% which is line with the figures shown in Table 7. A sample calculation is shown in full in Appendix H – Sample Heat Pump COP Calculations

4.4. Conclusion

It has been shown that using a heat recovery system to supply the indoor air to the air mixer is less effective that venting the indoor air directly into the air mixer. Conversely it was shown that using the waste heat from the compressor did lead to greater COP increases than solely using indoor air.

The greatest increases in COP were achieved using directly vented indoor air and waste heat from the compressor, with a maximum COP increase of 23% being achieved at an outdoor air temperature of -7°C. Likewise at -2°C and 2°C there were COP increases of 15% and 21% achieved respectively. It was interesting to note that from 7°C upwards, the maximum COP increase achieved was 6% whilst there were also instances where the COP decreased as opposed to increasing.

In terms of energy savings, naturally the greatest savings were achieved at the outdoor air temperatures which had the largest COP increases. The greatest energy saving calculated was 18% which occurred at the 21% COP increase. At the lowest registered outdoor air temperature, -20°C, an 8% energy saving was calculated whilst at the maximum outdoor temperature, 20°C, a 6% energy saving was calculated. It was interesting to note that despite these savings being very close in value, the energy savings in between the two temperature extremes varied greatly. The maximum energy savings indicated in the results were all greater than savings shown in Figure 9 for measures such as condensing boilers, loft insulation and cavity wall insulation.

5. Conclusion

It is possible to improve the coefficient of performance of heat pumps by utilising low exergy thermal sources to increase the source temperature at the evaporator, however there are many elements which will affect the extent to which the COP will be increased. The sensitivity of the heat pump being used will greatly determine how much scope there is for COP improvement, with results indicating that air-to-water heat pumps can be up to twice as sensitive to changes in source temperature as air-to-air heat pumps. It is also important to note that the temperature range at which the heat pump is operating will have an effect on the sensitivity of the chosen heat pump. Some models were more sensitive at lower source temperature whilst others were more sensitive in the medium source temperature range.

Once a suitable heat pump has been chosen, another element which will affect the potential to increase the COP of the heat pump is the way in which it is installed. Results within this report indicated that it is more favourable to directly vent air from a heat source to the evaporator unit as opposed to using a heat recovery system. It was also indicated that installing the heat pump in a manner which used the waste heat from the compressor to raise the source temperature was of additional benefit to the COP.

In the calculations performed in this report, the indoor air from the building along with waste heat from the compressor were chosen as the low exergy sources used to raise the source temperature of the heat pump, which resulted in a maximum COP increase of 23%. Should a low exergy thermal source with a higher temperature be chosen, the resulting COP increase could be greater, however changes in air flow rates within the building, depending on the source used or the occupancy levels within the building, may have additional effects on any potential COP increase. Some low exergy thermal sources which may provide an appropriately high temperature are more readily found in industrial or commercial buildings as opposed to domestic ones. Air extracted from chiller units or boiler rooms are examples of sources which are unlikely to be found in a regular dwelling.

When calculating the potential COP increases and corresponding energy savings for the chosen heat pump, the calculations were only undertaken for individual source temperatures. This range of temperatures was dictated by the information available in the technical data sheet for the chosen heat pump. For a more accurate representation of the potential increase in COP and energy savings over a length of time, in a realistic range of temperature, the seasonal coefficient of performance of the heat pump should be calculated as defined by EN 14825. The European Standard states that it is mandatory to calculate the SCOP for the heat pump using the "average" climate of Strasbourg. Given that the sensitivity study indicated that some heat pumps are more sensitive in lower source temperature ranges, it is also suggested that the colder climate of Helsinki also be used. For this report, the SCOP was unable to be calculated due to some information being unavailable, such as various power settings of the heat pump when in standby mode. These figures were unable to be sourced from the technical data sheets available for the chosen heat pump.

The calculations within this report were theoretical in nature and provided a guideline for the potential benefits of using low exergy thermal source to improve the COP of heat pumps, however more work could be done. In future work, it is suggested that dynamic simulations could be performed using a system such as TRNSYS in order to give a more in-depth calculation of COP improvements. By utilising a computer system, more detailed installations could be assessed over a sustained period of time, taking into account the stochastic nature of some low exergy thermal sources within buildings. It is also suggested that if sufficient time is available, manual testing of an actual heat pump could be performed in a laboratory to determine the real impact of using low exergy thermal sources to increase the source temperature.

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Appendices

Appendix A – Daikin Heat Pump Data

Table 11. Daikin heat pump unit specifications (Daikin, 2011)

Manufacturer	Series	Model Combination	Nominal Heating Capacity (kW)	Nominal Power Input - Heating (kW)
Daikin	VRV III	RXYQ5P9W1B + RXYQ-5P9	16	4
Daikin	VRV III	RXYQ5P9W1B + RXYQ-8P9	25	5.56
Daikin	VRV III	RXYQ5P9W1B + RXYQ-10P9	31.5	7.7
Daikin	VRV III	RXYQ5P9W1B + RXYQ-12P9	37.5	9.44
Daikin	VRV III	RXYQ5P9W1B + RXYQ-14P9	45	11.3
Daikin	VRV III	RXYQ5P9W1B + RXYQ-16P9	50	12.9
Daikin	VRV III	RXYQ5P9W1B + RXYQ-18P9	56.5	15.3

Table 12. Daikin temperature, heating capacity, power input and COP details (Daikin, 2011)

Series	Model Combination	Indoor Air Temperature (°C)	Outdoor Air Temperature (°C)	Heating Capacity (kW)	Power Input (kW)	COP	Carnot COP
VRV III	RXYQ5P9W1B + RXYQ-5P9	20	-19.8	10.5	3.22	3.26	7.36
VRV III	RXYQ5P9W1B + RXYQ-5P9	20	-18.8	10.8	3.31	3.26	7.55
VRV III	RXYQ5P9W1B + RXYQ-5P9	20	-16.7	11.4	3.48	3.28	7.98
VRV III	RXYQ5P9W1B + RXYQ-5P9	20	-13.7	12	3.63	3.31	8.69
VRV III	RXYQ5P9W1B + RXYQ-5P9	20	-11.8	12.7	3.77	3.37	9.21
VRV III	RXYQ5P9W1B + RXYQ-5P9	20	-9.8	13.3	3.89	3.42	9.83
VRV III	RXYQ5P9W1B + RXYQ-5P9	20	-9.5	13.6	3.95	3.44	9.93
VRV III	RXYQ5P9W1B + RXYQ-5P9	20	-8.5	13.9	4	3.48	10.28
VRV III	RXYQ5P9W1B + RXYQ-5P9	20	-7	14.4	4.08	3.53	10.85
VRV III	RXYQ5P9W1B + RXYQ-5P9	20	-5	15	4.18	3.59	11.72
VRV III	RXYQ5P9W1B + RXYQ-5P9	20	-3	15.6	4.26	3.66	12.74
VRV III	RXYQ5P9W1B + RXYQ-5P9	20	0	16.5	4.38	3.77	14.65
VRV III	RXYQ5P9W1B + RXYQ-5P9	20	3	17.4	4.49	3.88	17.24
VRV III	RXYQ5P9W1B + RXYQ-5P9	20	5	18	4.55	3.96	19.53
VRV III	RXYQ5P9W1B + RXYQ-5P9	20	7	18.6	4.61	4.03	22.54
VRV III	RXYQ5P9W1B + RXYQ-5P9	20	9	19.2	4.67	4.11	26.64
VRV III	RXYQ5P9W1B + RXYQ-5P9	20	11	19.8	4.72	4.19	32.56
VRV III	RXYQ5P9W1B + RXYQ-5P9	20	13	20.4	4.78	4.27	41.86
VRV III	RXYQ5P9W1B + RXYQ-5P9	20	15	20.8	4.74	4.39	58.60
VRV III	RXYQ5P9W1B + RXYQ-8P9	20	-19.8	16.1	4.3	3.74	7.36
VRV III	RXYQ5P9W1B + RXYQ-8P9	20	-18.8	16.6	4.43	3.75	7.55
VRV III	RXYQ5P9W1B + RXYQ-8P9	20	-16.7	17.6	4.66	3.78	7.98
VRV III	RXYQ5P9W1B + RXYQ-8P9	20	-13.7	18.5	4.87	3.80	8.69

VRV III	RXYQ5P9W1B + RXYQ-8P9	20	-11.8	19.5	5.16	3.78	9.21
VRV III	RXYQ5P9W1B + RXYQ-8P9	20	-9.8	20.4	5.23	3.90	9.83
VRV III	RXYQ5P9W1B + RXYQ-8P9	20	-9.5	20.9	5.32	3.93	9.93
VRV III	RXYQ5P9W1B + RXYQ-8P9	20	-8.5	21.4	5.38	3.98	10.28
VRV III	RXYQ5P9W1B + RXYQ-8P9	20	-7	22.1	5.49	4.03	10.85
VRV III	RXYQ5P9W1B + RXYQ-8P9	20	-5	23	5.63	4.09	11.72
VRV III	RXYQ5P9W1B + RXYQ-8P9	20	-3	23.9	5.75	4.16	12.74
VRV III	RXYQ5P9W1B + RXYQ-8P9	20	0	25.4	5.92	4.29	14.65
VRV III	RXYQ5P9W1B + RXYQ-8P9	20	3	26.8	6.06	4.42	17.24
VRV III	RXYQ5P9W1B + RXYQ-8P9	20	5	27.7	6.15	4.50	19.53
VRV III	RXYQ5P9W1B + RXYQ-8P9	20	7	28.6	6.23	4.59	22.54
VRV III	RXYQ5P9W1B + RXYQ-8P9	20	9	29.5	6.31	4.68	26.64
VRV III	RXYQ5P9W1B + RXYQ-8P9	20	11	30.4	6.39	4.76	32.56
VRV III	RXYQ5P9W1B + RXYQ-8P9	20	13	31.4	6.46	4.86	41.86
VRV III	RXYQ5P9W1B + RXYQ-8P9	20	15	32.3	6.53	4.95	58.60
VRV III	RXYQ5P9W1B + RXYQ-10P9	20	-19.8	20.2	6.21	3.25	7.36
VRV III	RXYQ5P9W1B + RXYQ-10P9	20	-18.8	20.6	6.32	3.26	7.55
VRV III	RXYQ5P9W1B + RXYQ-10P9	20	-16.7	21.3	6.55	3.25	7.98
VRV III	RXYQ5P9W1B + RXYQ-10P9	20	-13.7	22.2	6.79	3.27	8.69
VRV III	RXYQ5P9W1B + RXYQ-10P9	20	-11.8	23.2	7.13	3.25	9.21
VRV III	RXYQ5P9W1B + RXYQ-10P9	20	-9.8	24.2	7.28	3.32	9.83
VRV III	RXYQ5P9W1B + RXYQ-10P9	20	-9.5	24.8	7.4	3.35	9.93
VRV III	RXYQ5P9W1B + RXYQ-10P9	20	-8.5	25.4	7.51	3.38	10.28
VRV III	RXYQ5P9W1B + RXYQ-10P9	20	-7	26.3	7.69	3.42	10.85
VRV III	RXYQ5P9W1B + RXYQ-10P9	20	-5	27.6	7.93	3.48	11.72
VRV III	RXYQ5P9W1B + RXYQ-10P9	20	-3	29	8.14	3.56	12.74
VRV III	RXYQ5P9W1B + RXYQ-10P9	20	0	31.3	8.47	3.70	14.65
VRV III	RXYQ5P9W1B + RXYQ-10P9	20	3	33.7	8.77	3.84	17.24
VRV III	RXYQ5P9W1B + RXYQ-10P9	20	5	35.5	8.95	3.97	19.53
VRV III	RXYQ5P9W1B + RXYQ-10P9	20	7	37.3	9.13	4.09	22.54
VRV III	RXYQ5P9W1B + RXYQ-10P9	20	9	39.2	9.29	4.22	26.64
VRV III	RXYQ5P9W1B + RXYQ-10P9	20	11	41	9.38	4.37	32.56
VRV III	RXYQ5P9W1B + RXYQ-10P9	20	13	41	8.79	4.66	41.86
VRV III	RXYQ5P9W1B + RXYQ-10P9	20	15	41	8.28	4.95	58.60
VRV III	RXYQ5P9W1B + RXYQ-12P9	20	-19.8	20.6	5.02	4.10	7.36
VRV III	RXYQ5P9W1B + RXYQ-12P9	20	-18.8	20.9	5.15	4.06	7.55
VRV III	RXYQ5P9W1B + RXYQ-12P9	20	-16.7	21	5.43	3.87	7.98
VRV III	RXYQ5P9W1B + RXYQ-12P9	20	-13.7	22.6	5.72	3.95	8.69
VRV III	RXYQ5P9W1B + RXYQ-12P9	20	-11.8	23.6	6.02	3.92	9.21
VRV III	RXYQ5P9W1B + RXYQ-12P9	20	-9.8	24.7	6.31	3.91	9.83
VRV III	RXYQ5P9W1B + RXYQ-12P9	20	-9.5	25.2	6.46	3.90	9.93
VRV III	RXYQ5P9W1B + RXYQ-12P9	20	-8.5	25.8	6.6	3.91	10.28

VRV III	RXYQ5P9W1B + RXYQ-12P9	20	-7	26.7	6.81	3.92	10.85
VRV III	RXYQ5P9W1B + RXYQ-12P9	20	-5	28.1	7.1	3.96	11.72
VRV III	RXYQ5P9W1B + RXYQ-12P9	20	-3	29.4	7.36	3.99	12.74
VRV III	RXYQ5P9W1B + RXYQ-12P9	20	0	31.8	7.75	4.10	14.65
VRV III	RXYQ5P9W1B + RXYQ-12P9	20	3	34.3	8.11	4.23	17.24
VRV III	RXYQ5P9W1B + RXYQ-12P9	20	5	36	8.33	4.32	19.53
VRV III	RXYQ5P9W1B + RXYQ-12P9	20	7	37.8	8.54	4.43	22.54
VRV III	RXYQ5P9W1B + RXYQ-12P9	20	9	39.7	8.73	4.55	26.64
VRV III	RXYQ5P9W1B + RXYQ-12P9	20	11	41.7	8.92	4.67	32.56
VRV III	RXYQ5P9W1B + RXYQ-12P9	20	13	43.9	9.1	4.82	41.86
VRV III	RXYQ5P9W1B + RXYQ-12P9	20	15	46.1	9.27	4.97	58.60
VRV III	RXYQ5P9W1B + RXYQ-14P9	20	-19.8	27.9	8.38	3.33	7.36
VRV III	RXYQ5P9W1B + RXYQ-14P9	20	-18.8	28.4	8.55	3.32	7.55
VRV III	RXYQ5P9W1B + RXYQ-14P9	20	-16.7	29.6	8.89	3.33	7.98
VRV III	RXYQ5P9W1B + RXYQ-14P9	20	-13.7	30.8	9.24	3.33	8.69
VRV III	RXYQ5P9W1B + RXYQ-14P9	20	-11.8	32.1	9.6	3.34	9.21
VRV III	RXYQ5P9W1B + RXYQ-14P9	20	-9.8	33.6	9.95	3.38	9.83
VRV III	RXYQ5P9W1B + RXYQ-14P9	20	-9.5	34.4	10.13	3.40	9.93
VRV III	RXYQ5P9W1B + RXYQ-14P9	20	-8.5	35.1	10.28	3.41	10.28
VRV III	RXYQ5P9W1B + RXYQ-14P9	20	-7	36.4	10.54	3.45	10.85
VRV III	RXYQ5P9W1B + RXYQ-14P9	20	-5	38.2	10.9	3.50	11.72
VRV III	RXYQ5P9W1B + RXYQ-14P9	20	-3	40.1	11.2	3.58	12.74
VRV III	RXYQ5P9W1B + RXYQ-14P9	20	0	43.2	11.6	3.72	14.65
VRV III	RXYQ5P9W1B + RXYQ-14P9	20	3	46.5	12.1	3.84	17.24
VRV III	RXYQ5P9W1B + RXYQ-14P9	20	5	48.8	12.3	3.97	19.53
VRV III	RXYQ5P9W1B + RXYQ-14P9	20	7	51.2	12.6	4.06	22.54
VRV III	RXYQ5P9W1B + RXYQ-14P9	20	9	53.7	12.8	4.20	26.64
VRV III	RXYQ5P9W1B + RXYQ-14P9	20	11	56.4	13	4.34	32.56
VRV III	RXYQ5P9W1B + RXYQ-14P9	20	13	58.5	12.9	4.53	41.86
VRV III	RXYQ5P9W1B + RXYQ-14P9	20	15	58.5	12.2	4.80	58.60
VRV III	RXYQ5P9W1B + RXYQ-16P9	20	-19.8	30.4	9.09	3.34	7.36
VRV III	RXYQ5P9W1B + RXYQ-16P9	20	-18.8	31	9.28	3.34	7.55
VRV III	RXYQ5P9W1B + RXYQ-16P9	20	-16.7	32.2	9.68	3.33	7.98
VRV III	RXYQ5P9W1B + RXYQ-16P9	20	-13.7	33.5	10.08	3.32	8.69
VRV III	RXYQ5P9W1B + RXYQ-16P9	20	-11.8	35	10.48	3.34	9.21
VRV III	RXYQ5P9W1B + RXYQ-16P9	20	-9.8	36.6	10.89	3.36	9.83
VRV III	RXYQ5P9W1B + RXYQ-16P9	20	-9.5	37.5	11.09	3.38	9.93
VRV III	RXYQ5P9W1B + RXYQ-16P9	20	-8.5	38.3	11.27	3.40	10.28
VRV III	RXYQ5P9W1B + RXYQ-16P9	20	-7	39.7	11.6	3.42	10.85
VRV III	RXYQ5P9W1B + RXYQ-16P9	20	-5	41.6	11.9	3.50	11.72
VRV III	RXYQ5P9W1B + RXYQ-16P9	20	-3	43.6	12.3	3.54	12.74
VRV III	RXYQ5P9W1B + RXYQ-16P9	20	0	47	12.8	3.67	14.65

VRV III	RXYQ5P9W1B + RXYQ-16P9	20	3	50.6	13.3	3.80	17.24
VRV III	RXYQ5P9W1B + RXYQ-16P9	20	5	53.1	13.6	3.90	19.53
VRV III	RXYQ5P9W1B + RXYQ-16P9	20	7	55.8	13.9	4.01	22.54
VRV III	RXYQ5P9W1B + RXYQ-16P9	20	9	58.5	14.1	4.15	26.64
VRV III	RXYQ5P9W1B + RXYQ-16P9	20	11	61.4	14.4	4.26	32.56
VRV III	RXYQ5P9W1B + RXYQ-16P9	20	13	64.5	14.6	4.42	41.86
VRV III	RXYQ5P9W1B + RXYQ-16P9	20	15	65	13.9	4.68	58.60
VRV III	RXYQ5P9W1B + RXYQ-18P9	20	-19.8	31.2	8.14	3.83	7.36
VRV III	RXYQ5P9W1B + RXYQ-18P9	20	-18.8	31.8	8.37	3.80	7.55
VRV III	RXYQ5P9W1B + RXYQ-18P9	20	-16.7	33	8.83	3.74	7.98
VRV III	RXYQ5P9W1B + RXYQ-18P9	20	-13.7	34.3	9.3	3.69	8.69
VRV III	RXYQ5P9W1B + RXYQ-18P9	20	-11.8	35.8	9.8	3.65	9.21
VRV III	RXYQ5P9W1B + RXYQ-18P9	20	-9.8	37.5	10.3	3.64	9.83
VRV III	RXYQ5P9W1B + RXYQ-18P9	20	-9.5	38.3	10.5	3.65	9.93
VRV III	RXYQ5P9W1B + RXYQ-18P9	20	-8.5	39.2	10.7	3.66	10.28
VRV III	RXYQ5P9W1B + RXYQ-18P9	20	-7	40.6	11.1	3.66	10.85
VRV III	RXYQ5P9W1B + RXYQ-18P9	20	-5	42.6	11.5	3.70	11.72
VRV III	RXYQ5P9W1B + RXYQ-18P9	20	-3	44.6	11.9	3.75	12.74
VRV III	RXYQ5P9W1B + RXYQ-18P9	20	0	48.1	12.6	3.82	14.65
VRV III	RXYQ5P9W1B + RXYQ-18P9	20	3	51.7	13.1	3.95	17.24
VRV III	RXYQ5P9W1B + RXYQ-18P9	20	5	54.3	13.5	4.02	19.53
VRV III	RXYQ5P9W1B + RXYQ-18P9	20	7	57	13.8	4.13	22.54
VRV III	RXYQ5P9W1B + RXYQ-18P9	20	9	59.8	14.2	4.21	26.64
VRV III	RXYQ5P9W1B + RXYQ-18P9	20	11	62.7	14.5	4.32	32.56
VRV III	RXYQ5P9W1B + RXYQ-18P9	20	13	65.9	14.8	4.45	41.86
VRV III	RXYQ5P9W1B + RXYQ-18P9	20	15	69.1	15	4.61	58.60

Appendix B – Worcester Bosch Heat Pump Data

Table 13. Worcester Bosch heat pump unit specifications (Worcester Bosch Group, 2013)

Manufacturer	Series	Model	Nominal Heating Capacity (kW)	Nominal Power Input - Heating (kW)
Worcester Bosch	Greensource	7-716-150-179	4	1.3

Table 14. Worcester Bosch Greensource Heating capacities, power inputs and COPs (Worcester Bosch Group, 2013)

Indoor Air Temperature (°C)	Outdoor Air Temperature (°C)	Heating Capacity (kW)	Power Input (kW)	COP	Carnot COP
20	-15	2.5	2.5	1.00	8.37
20	-7	3.2	2.5	1.28	10.85
20	2	3.5	2.5	1.40	16.28
20	7	4.7	2.5	1.88	22.54

Appendix C – Samsung Heat Pump Data

Table 15. Samsung heat pump unit specifications (Samsung, 2015)

Manufacturer	Series	Model Combination	Nominal Heating Capacity (kW)	Nominal Power Input - Heating (kW)
Samsung	Slim 1 Way Cassette	AC026FCADEH/EU + AC026FB1DEH/EU	4.6	1.3
Samsung	Slim 1 Way Cassette	AC035FCADEH/EU + AC035FB1DEH/EU	4.75	1.39
Samsung	Mini 4 Way Cassette	AC026FCADEH/EU + AC026FBNDEH/EU	4.6	1.4
Samsung	Mini 4 Way Cassette	AC035FCADEH/EU + AC035FBNDEH/EU	5	1.4
Samsung	Mini 4 Way Cassette	AC052FCADEH/EU + AC052FBNDEH/EU	7.5	2.4
Samsung	Mini 4 Way Cassette	AC060FCADEH/EU + AC060FBNDEH/EU	9	3.6
Samsung	Mini 4 Way Cassette	AC071FCADEH/EU + AC071FBNDEH/EU	10	3.8

Table 16. Samsung heating capacities, power inputs and COPs (Samsung, 2015)

Series	Model Combination	Indoor Air Temperature (°C)	Outdoor Air Temperature (°C)	Heating Capacity (kW)	Power Input (kW)	COP	Carnot COP
Slim 1 Way Cassette	AC026FCADEH/EU + AC026FB1DEH/EU	20	-15	2.31	1.1	2.10	8.37
Slim 1 Way Cassette	AC026FCADEH/EU + AC026FB1DEH/EU	20	-10	2.72	1.07	2.54	9.77
Slim 1 Way Cassette	AC026FCADEH/EU + AC026FB1DEH/EU	20	7	3.3	0.91	3.63	22.54
Slim 1 Way Cassette	AC026FCADEH/EU + AC026FB1DEH/EU	20	24	3.52	0.96	3.67	-73.25
Slim 1 Way Cassette	AC035FCADEH/EU + AC035FB1DEH/EU	20	-15	2.51	1.41	1.78	8.37
Slim 1 Way Cassette	AC035FCADEH/EU + AC035FB1DEH/EU	20	-10	3.31	1.38	2.40	9.77
Slim 1 Way Cassette	AC035FCADEH/EU + AC035FB1DEH/EU	20	7	4	1.16	3.45	22.54
Slim 1 Way Cassette	AC035FCADEH/EU + AC035FB1DEH/EU	20	24	4.2	1.24	3.39	-73.25
Mini 4 Way Cassette	AC026FCADEH/EU + AC026FBNDEH/EU	20	-15	2.32	1.05	2.21	8.37

Mini 4 Way Cassette	AC026FCADEH/EU + AC026FBNDEH/EU	20	-10	2.65	1.1	2.41	9.77
Mini 4 Way Cassette	AC026FCADEH/EU + AC026FBNDEH/EU	20	7	3.3	0.9	3.67	22.54
Mini 4 Way Cassette	AC026FCADEH/EU + AC026FBNDEH/EU	20	24	4.11	1.02	4.03	-73.25
Mini 4 Way Cassette	AC035FCADEH/EU + AC035FBNDEH/EU	20	-15	2.41	1.12	2.15	8.37
Mini 4 Way Cassette	AC035FCADEH/EU + AC035FBNDEH/EU	20	-10	3.02	1.25	2.42	9.77
Mini 4 Way Cassette	AC035FCADEH/EU + AC035FBNDEH/EU	20	7	4.02	1.11	3.62	22.54
Mini 4 Way Cassette	AC035FCADEH/EU + AC035FBNDEH/EU	20	24	4.98	1.5	3.32	-73.25
Mini 4 Way Cassette	AC052FCADEH/EU + AC052FBNDEH/EU	20	-15	4.2	2.05	2.05	8.37
Mini 4 Way Cassette	AC052FCADEH/EU + AC052FBNDEH/EU	20	-10	4.58	1.91	2.40	9.77
Mini 4 Way Cassette	AC052FCADEH/EU + AC052FBNDEH/EU	20	7	5.5	1.52	3.62	22.54
Mini 4 Way Cassette	AC052FCADEH/EU + AC052FBNDEH/EU	20	24	6.25	1.54	4.06	-73.25
Mini 4 Way Cassette	AC060FCADEH/EU + AC060FBNDEH/EU	20	-15	5.15	2.84	1.81	8.37
Mini 4 Way Cassette	AC060FCADEH/EU + AC060FBNDEH/EU	20	-10	6.02	2.82	2.13	9.77
Mini 4 Way Cassette	AC060FCADEH/EU + AC060FBNDEH/EU	20	7	7	2.18	3.21	22.54
Mini 4 Way Cassette	AC060FCADEH/EU + AC060FBNDEH/EU	20	24	8.25	2.25	3.67	-73.25
Mini 4 Way Cassette	AC071FCADEH/EU + AC071FBNDEH/EU	20	-15	4.86	2.78	1.75	8.37
Mini 4 Way Cassette	AC071FCADEH/EU + AC071FBNDEH/EU	20	-10	6.1	2.91	2.10	9.77
Mini 4 Way Cassette	AC071FCADEH/EU + AC071FBNDEH/EU	20	7	7.5	2.32	3.23	22.54
Mini 4 Way Cassette	AC071FCADEH/EU + AC071FBNDEH/EU	20	24	7.8	2.15	3.63	-73.25

Appendix D – Kingspan Heat Pump Data

Table 17. Kingspan heat pump unit specification (Kingspan, 2011)

Manufacturer	Series	Model	Nominal Heating Capacity (kW)	Nominal Power Input - Heating (kW)
Kingspan	Aeromax Plus	4kW	4.1	1.01
Kingspan	Aeromax Plus	6kW	5.8	1.37
Kingspan	Aeromax Plus	8kW	7.2	1.82
Kingspan	Aeromax Plus	12kW	11.9	3.01
Kingspan	Aeromax Plus	15kW	14.5	3.57

Table 18. Kingspan heating capacities, power inputs and COPs (Kingspan, 2011)

Series	Model	Output Water Temperature (°C)	Outdoor Air Temperature (°C)	Heating Capacity (kW)	Power Input (kW)	COP	Carnot COP
Aeromax Plus	4kW	35	-3	3.01	0.97	3.09	8.11
Aeromax Plus	4kW	35	0	3.26	1.03	3.15	8.80
Aeromax Plus	4kW	35	2	3.5	1.13	3.10	9.33
Aeromax Plus	4kW	35	7	4.1	1.01	4.06	11.00
Aeromax Plus	6kW	35	-3	3.67	1.25	2.93	8.11
Aeromax Plus	6kW	35	0	3.98	1.34	2.98	8.80
Aeromax Plus	6kW	35	2	4.19	1.36	3.08	9.33
Aeromax Plus	6kW	35	7	5.81	1.38	4.22	11.00
Aeromax Plus	8kW	35	-3	4.73	1.68	2.81	8.11
Aeromax Plus	8kW	35	0	5.14	1.74	2.95	8.80
Aeromax Plus	8kW	35	2	5.41	1.80	3.00	9.33
Aeromax Plus	8kW	35	7	7.19	1.83	3.92	11.00
Aeromax Plus	12kW	35	-3	7.8	2.71	2.88	8.11
Aeromax Plus	12kW	35	0	8.47	2.80	3.02	8.80
Aeromax Plus	12kW	35	2	8.72	2.79	3.13	9.33
Aeromax Plus	12kW	35	7	11.8	2.97	3.98	11.00
Aeromax Plus	15kW	35	-3	9.06	3.18	2.85	8.11
Aeromax Plus	15kW	35	0	9.81	3.19	3.08	8.80
Aeromax Plus	15kW	35	2	10.2	3.19	3.20	9.33
Aeromax Plus	15kW	35	7	14.5	3.57	4.06	11.00

Appendix E – Toshiba Heat Pump Data

Table 19. Toshiba heat pump unit specifications (Toshiba, 2010b)

Manufacturer	Series	Model Combination	Nominal Heating Capacity (kW)	Nominal Power Input - Heating (kW)
Toshiba	Estia	HWS-803H-E + HWS-803XWH**-E	8	1.82
Toshiba	Estia	HWS-1103H-E + HWS-1403XWH**-E	11.2	2.35
Toshiba	Estia	HWS-1403H-E + HWS-1403XWH**-E	14	3.11

Table 20. Toshiba heating capacities, power inputs and COPs (Toshiba, 2010b)

Series	Model Combination	Output Water Temperature (°C)	Outdoor Air Temperature (°C)	Heating Capacity (kW)	Power Input (kW)	COP	Carnot COP
Estia	HWS-803H-E + HWS-803XWH**-E	35	-20	3.83	1.82	2.10	5.60
Estia	HWS-803H-E + HWS-803XWH**-E	35	-15	4.54	1.9	2.39	6.16
Estia	HWS-803H-E + HWS-803XWH**-E	35	-7	5.3	2.21	2.40	7.33

Estia	HWS-803H-E + HWS-803XWH**-E	35	-2	6.11	2.26	2.70	8.32
Estia	HWS-803H-E + HWS-803XWH**-E	35	2	6.75	2.28	2.96	9.33
Estia	HWS-803H-E + HWS-803XWH**-E	35	7	8.78	2.07	4.24	11.00
Estia	HWS-803H-E + HWS-803XWH**-E	35	10	9.29	2.03	4.58	12.32
Estia	HWS-803H-E + HWS-803XWH**-E	35	12	9.81	2.02	4.86	13.39
Estia	HWS-803H-E + HWS-803XWH**-E	35	15	10.6	2.02	5.25	15.40
Estia	HWS-803H-E + HWS-803XWH**-E	35	20	11.99	2.01	5.97	20.53
Estia	HWS-1103H-E + HWS-1403XWH**-E	35	-20	5.48	2.97	1.85	5.60
Estia	HWS-1103H-E + HWS-1403XWH**-E	35	-15	6.86	3.09	2.22	6.16
Estia	HWS-1103H-E + HWS-1403XWH**-E	35	-7	8	3.4	2.35	7.33
Estia	HWS-1103H-E + HWS-1403XWH**-E	35	-2	9.9	3.35	2.96	8.32
Estia	HWS-1103H-E + HWS-1403XWH**-E	35	2	10.55	3.3	3.20	9.33
Estia	HWS-1103H-E + HWS-1403XWH**-E	35	7	14.97	3.23	4.63	11.00
Estia	HWS-1103H-E + HWS-1403XWH**-E	35	10	15.87	3.21	4.94	12.32
Estia	HWS-1103H-E + HWS-1403XWH**-E	35	12	16.62	3	5.54	13.39
Estia	HWS-1103H-E + HWS-1403XWH**-E	35	15	17.7	3.19	5.55	15.40
Estia	HWS-1103H-E + HWS-1403XWH**-E	35	20	20.01	3.17	6.31	20.53
Estia	HWS-1403H-E + HWS-1403XWH**-E	35	-20	6.18	3.5	1.77	5.60
Estia	HWS-1403H-E + HWS-1403XWH**-E	35	-15	7.94	3.69	2.15	6.16
Estia	HWS-1403H-E + HWS-1403XWH**-E	35	-7	9.37	4.1	2.29	7.33
Estia	HWS-1403H-E + HWS-1403XWH**-E	35	-2	10.93	4.04	2.71	8.32
Estia	HWS-1403H-E + HWS-1403XWH**-E	35	2	11.56	3.98	2.90	9.33
Estia	HWS-1403H-E + HWS-1403XWH**-E	35	7	17.08	3.94	4.34	11.00
Estia	HWS-1403H-E + HWS-1403XWH**-E	35	10	17.93	3.94	4.55	12.32
Estia	HWS-1403H-E + HWS-1403XWH**-E	35	12	18.96	3.95	4.80	13.39
Estia	HWS-1403H-E + HWS-1403XWH**-E	35	15	20.09	3.98	5.05	15.40
Estia	HWS-1403H-E + HWS-1403XWH**-E	35	20	21.87	3.75	5.83	20.53

Appendix F – Extrapolated Heat Pump Data

Table 21. Extrapolated COP figures

ID Tag	Sink Temperature (°C)	Source Temperature (°C)	Temperature Difference (ΔT)	Heating Capacity (kW)	Power Input (kW)	COP	Carnot COP
D1	20	-19.8	39.8	10.5	3.22	3.26	7.36
D1	20	-18.8	38.8	10.8	3.31	3.26	7.55
D1	20	-16.7	36.7	11.4	3.48	3.28	7.98
D1	20	-15	35			3.29	8.37
D1	20	-13.7	33.7	12	3.63	3.31	8.69
D1	20	-11.8	31.8	12.7	3.77	3.37	9.21
D1	20	-10	10			3.39	29.30

D1	20	-9.8	29.8	13.3	3.89	3.42	9.83
D1	20	-9.5	29.5	13.6	3.95	3.44	9.93
D1	20	-8.5	28.5	13.9	4	3.48	10.28
D1	20	-7	27	14.4	4.08	3.53	10.85
D1	20	-5	25	15	4.18	3.59	11.72
D1	20	-3	23	15.6	4.26	3.66	12.74
D1	20	-2	22			3.71	13.32
D1	20	0	20	16.5	4.38	3.77	14.65
D1	20	2	18			3.82	16.28
D1	20	3	17	17.4	4.49	3.88	17.24
D1	20	5	15	18	4.55	3.96	19.53
D1	20	7	13	18.6	4.61	4.03	22.54
D1	20	9	11	19.2	4.67	4.11	26.64
D1	20	10	10			4.15	29.30
D1	20	11	9	19.8	4.72	4.19	32.56
D1	20	12	8			4.23	36.63
D1	20	13	7	20.4	4.78	4.27	41.86
D1	20	15	5	20.8	4.74	4.39	58.60
D2	20	-19.8	39.8	16.1	4.3	3.74	7.36
D2	20	-18.8	38.8	16.6	4.43	3.75	7.55
D2	20	-16.7	36.7	17.6	4.66	3.78	7.98
D2	20	-15	35			3.79	8.37
D2	20	-13.7	33.7	18.5	4.87	3.80	8.69
D2	20	-11.8	31.8	19.5	5.16	3.78	9.21
D2	20	-10	30			3.84	9.77
D2	20	-9.8	29.8	20.4	5.23	3.90	9.83
D2	20	-9.5	29.5	20.9	5.32	3.93	9.93
D2	20	-8.5	28.5	21.4	5.38	3.98	10.28
D2	20	-7	27	22.1	5.49	4.03	10.85
D2	20	-5	25	23	5.63	4.09	11.72
D2	20	-3	23	23.9	5.75	4.16	12.74
D2	20	-2	22			4.22	13.32
D2	20	0	20	25.4	5.92	4.29	14.65
D2	20	2	18			4.36	16.28
D2	20	3	17	26.8	6.06	4.42	17.24
D2	20	5	15	27.7	6.15	4.50	19.53
D2	20	7	13	28.6	6.23	4.59	22.54
D2	20	9	11	29.5	6.31	4.68	26.64
D2	20	10	10			4.72	29.30
D2	20	11	9	30.4	6.39	4.76	32.56
D2	20	12	8			4.81	36.63
D2	20	13	7	31.4	6.46	4.86	41.86

D2	20	15	5	32.3	6.53	4.95	58.60
D3	20	-19.8	39.8	20.2	6.21	3.25	7.36
D3	20	-18.8	38.8	20.6	6.32	3.26	7.55
D3	20	-16.7	36.7	21.3	6.55	3.25	7.98
D3	20	-15	35			3.26	8.37
D3	20	-13.7	33.7	22.2	6.79	3.27	8.69
D3	20	-11.8	31.8	23.2	7.13	3.25	9.21
D3	20	-10	30			3.29	9.77
D3	20	-9.8	29.8	24.2	7.28	3.32	9.83
D3	20	-9.5	29.5	24.8	7.4	3.35	9.93
D3	20	-8.5	28.5	25.4	7.51	3.38	10.28
D3	20	-7	27	26.3	7.69	3.42	10.85
D3	20	-5	25	27.6	7.93	3.48	11.72
D3	20	-3	23	29	8.14	3.56	12.74
D3	20	-2	22			3.63	13.32
D3	20	0	20	31.3	8.47	3.70	14.65
D3	20	2	18			3.77	16.28
D3	20	3	17	33.7	8.77	3.84	17.24
D3	20	5	15	35.5	8.95	3.97	19.53
D3	20	7	13	37.3	9.13	4.09	22.54
D3	20	9	11	39.2	9.29	4.22	26.64
D3	20	10	10			4.30	29.30
D3	20	11	9	41	9.38	4.37	32.56
D3	20	12	8			4.52	36.63
D3	20	13	7	41	8.79	4.66	41.86
D3	20	15	5	41	8.28	4.95	58.60
D4	20	-19.8	39.8	20.6	5.02	4.10	7.36
D4	20	-18.8	38.8	20.9	5.15	4.06	7.55
D4	20	-16.7	36.7	21	5.43	3.87	7.98
D4	20	-15	35			3.91	8.37
D4	20	-13.7	33.7	22.6	5.72	3.95	8.69
D4	20	-11.8	31.8	23.6	6.02	3.92	9.21
D4	20	-10	30			3.92	9.77
D4	20	-9.8	29.8	24.7	6.31	3.91	9.83
D4	20	-9.5	29.5	25.2	6.46	3.90	9.93
D4	20	-8.5	28.5	25.8	6.6	3.91	10.28
D4	20	-7	27	26.7	6.81	3.92	10.85
D4	20	-5	25	28.1	7.1	3.96	11.72
D4	20	-3	23	29.4	7.36	3.99	12.74
D4	20	-2	22			4.05	13.32
D4	20	0	20	31.8	7.75	4.10	14.65
D4	20	2	18			4.17	16.28

D4	20	3	17	34.3	8.11	4.23	17.24
D4	20	5	15	36	8.33	4.32	19.53
D4	20	7	13	37.8	8.54	4.43	22.54
D4	20	9	11	39.7	8.73	4.55	26.64
D4	20	10	10			4.61	29.30
D4	20	11	9	41.7	8.92	4.67	32.56
D4	20	12	8			4.75	36.63
D4	20	13	7	43.9	9.1	4.82	41.86
D4	20	15	5	46.1	9.27	4.97	58.60
D5	20	-19.8	39.8	27.9	8.38	3.33	7.36
D5	20	-18.8	38.8	28.4	8.55	3.32	7.55
D5	20	-16.7	36.7	29.6	8.89	3.33	7.98
D5	20	-15	35			3.33	8.37
D5	20	-13.7	33.7	30.8	9.24	3.33	8.69
D5	20	-11.8	31.8	32.1	9.6	3.34	9.21
D5	20	-10	30			3.36	9.77
D5	20	-9.8	29.8	33.6	9.95	3.38	9.83
D5	20	-9.5	29.5	34.4	10.13	3.40	9.93
D5	20	-8.5	28.5	35.1	10.28	3.41	10.28
D5	20	-7	27	36.4	10.54	3.45	10.85
D5	20	-5	25	38.2	10.9	3.50	11.72
D5	20	-3	23	40.1	11.2	3.58	12.74
D5	20	-2	22			3.65	13.32
D5	20	0	20	43.2	11.6	3.72	14.65
D5	20	2	18			3.78	16.28
D5	20	3	17	46.5	12.1	3.84	17.24
D5	20	5	15	48.8	12.3	3.97	19.53
D5	20	7	13	51.2	12.6	4.06	22.54
D5	20	9	11	53.7	12.8	4.20	26.64
D5	20	10	10			4.27	29.30
D5	20	11	9	56.4	13	4.34	32.56
D5	20	12	8			4.44	36.63
D5	20	13	7	58.5	12.9	4.53	41.86
D5	20	15	5	58.5	12.2	4.80	58.60
D6	20	-19.8	39.8	30.4	9.09	3.34	7.36
D6	20	-18.8	38.8	31	9.28	3.34	7.55
D6	20	-16.7	36.7	32.2	9.68	3.33	7.98
D6	20	-15	35			3.32	8.37
D6	20	-13.7	33.7	33.5	10.08	3.32	8.69
D6	20	-11.8	31.8	35	10.48	3.34	9.21
D6	20	-10	30			3.35	9.77
D6	20	-9.8	29.8	36.6	10.89	3.36	9.83

D6	20	-9.5	29.5	37.5	11.09	3.38	9.93
D6	20	-8.5	28.5	38.3	11.27	3.40	10.28
D6	20	-7	27	39.7	11.6	3.42	10.85
D6	20	-5	25	41.6	11.9	3.50	11.72
D6	20	-3	23	43.6	12.3	3.54	12.74
D6	20	-2	22			3.61	13.32
D6	20	0	20	47	12.8	3.67	14.65
D6	20	2	18			3.74	16.28
D6	20	3	17	50.6	13.3	3.80	17.24
D6	20	5	15	53.1	13.6	3.90	19.53
D6	20	7	13	55.8	13.9	4.01	22.54
D6	20	9	11	58.5	14.1	4.15	26.64
D6	20	10	10			4.21	29.30
D6	20	11	9	61.4	14.4	4.26	32.56
D6	20	12	8			4.34	36.63
D6	20	13	7	64.5	14.6	4.42	41.86
D6	20	15	5	65	13.9	4.68	58.60
D7	20	-19.8	39.8	31.2	8.14	3.83	7.36
D7	20	-18.8	38.8	31.8	8.37	3.80	7.55
D7	20	-16.7	36.7	33	8.83	3.74	7.98
D7	20	-15	35			3.71	8.37
D7	20	-13.7	33.7	34.3	9.3	3.69	8.69
D7	20	-11.8	31.8	35.8	9.8	3.65	9.21
D7	20	-10	30			3.65	9.77
D7	20	-9.8	29.8	37.5	10.3	3.64	9.83
D7	20	-9.5	29.5	38.3	10.5	3.65	9.93
D7	20	-8.5	28.5	39.2	10.7	3.66	10.28
D7	20	-7	27	40.6	11.1	3.66	10.85
D7	20	-5	25	42.6	11.5	3.70	11.72
D7	20	-3	23	44.6	11.9	3.75	12.74
D7	20	-2	22			3.78	13.32
D7	20	0	20	48.1	12.6	3.82	14.65
D7	20	2	18			3.88	16.28
D7	20	3	17	51.7	13.1	3.95	17.24
D7	20	5	15	54.3	13.5	4.02	19.53
D7	20	7	13	57	13.8	4.13	22.54
D7	20	9	11	59.8	14.2	4.21	26.64
D7	20	10	10			4.27	29.30
D7	20	11	9	62.7	14.5	4.32	32.56
D7	20	12	8			4.39	36.63
D7	20	13	7	65.9	14.8	4.45	41.86
D7	20	15	5	69.1	15	4.61	58.60

K1	35	-3	38	3.01	0.97411	3.09	8.11
K1	35	-2	37			3.12	8.32
K1	35	0	35	3.26	1.034921	3.15	8.80
K1	35	2	33	3.5	1.129032	3.10	9.33
K1	35	3	32			3.34	9.63
K1	35	5	30			3.82	10.27
K1	35	7	28	4.1	1.009852	4.06	11.00
K2	35	-3	38	3.67	1.25256	2.93	8.11
K2	35	-2	37			2.96	8.32
K2	35	0	35	3.98	1.33557	2.98	8.80
K2	35	2	33	4.19	1.36039	3.08	9.33
K2	35	3	32			3.37	9.63
K2	35	5	30			3.94	10.27
K2	35	7	28	5.81	1.376777	4.22	11.00
K3	35	-3	38	4.73	1.683274	2.81	8.11
K3	35	-2	37			2.88	8.32
K3	35	0	35	5.14	1.742373	2.95	8.80
K3	35	2	33	5.41	1.803333	3.00	9.33
K3	35	3	32			3.23	9.63
K3	35	5	30			3.69	10.27
K3	35	7	28	7.19	1.834184	3.92	11.00
K4	35	-3	38	7.8	2.708333	2.88	8.11
K4	35	-2	37			2.95	8.32
K4	35	0	35	8.47	2.804636	3.02	8.80
K4	35	2	33	8.72	2.785942	3.13	9.33
K4	35	3	32			3.34	9.63
K4	35	5	30			3.77	10.27
K4	35	7	28	11.82	2.969849	3.98	11.00
K5	35	-3	38	9.06	3.178947	2.85	8.11
K5	35	-2	37			2.97	8.32
K5	35	0	35	9.81	3.185065	3.08	8.80
K5	35	2	33	10.2	3.1875	3.20	9.33
K5	35	3	32			3.42	9.63
K5	35	5	30			3.85	10.27
K5	35	7	28	14.5	3.571429	4.06	11.00
S1	20	-15	35	2.31	1.1	2.10	8.37
S1	20	-13.7	33.7			2.21	8.69
S1	20	-11.8	31.8			2.43	9.21
S1	20	-10	30	2.72	1.07	2.54	9.77
S1	20	-9.8	29.8			2.68	9.83
S1	20	-9.5	29.5			2.75	9.93
S1	20	-8.5	28.5			2.81	10.28

S1	20	-7	27			2.88	10.85
S1	20	-5	25			3.02	11.72
S1	20	-3	23			3.08	12.74
S1	20	-2	22			3.22	13.32
S1	20	0	20			3.29	14.65
S1	20	2	18			3.36	16.28
S1	20	3	17			3.42	17.24
S1	20	5	15			3.56	19.53
S1	20	7	13	3.3	0.91	3.63	22.54
S1	20	9	11			3.63	26.64
S1	20	10	10			3.64	29.30
S1	20	11	9			3.64	32.56
S1	20	12	8			3.65	36.63
S1	20	13	7			3.65	41.86
S1	20	15	5			3.66	58.60
S1	20	20	0			3.66	#DIV/0!
S1	20	24	4	3.52	0.96	3.67	73.25
S2	20	-15	35	2.51	1.41	1.78	8.37
S2	20	-13.7	33.7			1.93	8.69
S2	20	-11.8	31.8			2.24	9.21
S2	20	-10	30	3.31	1.38	2.40	9.77
S2	20	-9.8	29.8			2.53	9.83
S2	20	-9.5	29.5			2.60	9.93
S2	20	-8.5	28.5			2.66	10.28
S2	20	-7	27			2.73	10.85
S2	20	-5	25			2.86	11.72
S2	20	-3	23			2.92	12.74
S2	20	-2	22			3.05	13.32
S2	20	0	20			3.12	14.65
S2	20	2	18			3.19	16.28
S2	20	3	17			3.25	17.24
S2	20	5	15			3.38	19.53
S2	20	7	13	4	1.16	3.45	22.54
S2	20	9	11			3.44	26.64
S2	20	10	10			3.43	29.30
S2	20	11	9			3.43	32.56
S2	20	12	8			3.42	36.63
S2	20	13	7			3.41	41.86
S2	20	15	5			3.40	58.60
S2	20	20	0			3.39	#DIV/0!
S2	20	24	4	4.2	1.24	3.39	73.25
S3	20	-15	35	2.32	1.05	2.21	8.37

S3	20	-13.7	33.7			2.26	8.69
S3	20	-11.8	31.8			2.36	9.21
S3	20	-10	30	2.65	1.1	2.41	9.77
S3	20	-9.8	29.8			2.57	9.83
S3	20	-9.5	29.5			2.64	9.93
S3	20	-8.5	28.5			2.72	10.28
S3	20	-7	27			2.80	10.85
S3	20	-5	25			2.96	11.72
S3	20	-3	23			3.04	12.74
S3	20	-2	22			3.20	13.32
S3	20	0	20			3.27	14.65
S3	20	2	18			3.35	16.28
S3	20	3	17			3.43	17.24
S3	20	5	15			3.59	19.53
S3	20	7	13	3.3	0.9	3.67	22.54
S3	20	9	11			3.71	26.64
S3	20	10	10			3.76	29.30
S3	20	11	9			3.80	32.56
S3	20	12	8			3.85	36.63
S3	20	13	7			3.89	41.86
S3	20	15	5			3.94	58.60
S3	20	20	0			3.98	#DIV/0!
S3	20	24	4	4.11	1.02	4.03	73.25
S4	20	-15	35	2.41	1.12	2.15	8.37
S4	20	-13.7	33.7			2.22	8.69
S4	20	-11.8	31.8			2.35	9.21
S4	20	-10	30	3.02	1.25	2.42	9.77
S4	20	-9.8	29.8			2.57	9.83
S4	20	-9.5	29.5			2.64	9.93
S4	20	-8.5	28.5			2.72	10.28
S4	20	-7	27			2.79	10.85
S4	20	-5	25			2.94	11.72
S4	20	-3	23			3.02	12.74
S4	20	-2	22			3.17	13.32
S4	20	0	20			3.24	14.65
S4	20	2	18			3.32	16.28
S4	20	3	17			3.40	17.24
S4	20	5	15			3.55	19.53
S4	20	7	13	4.02	1.11	3.62	22.54
S4	20	9	11			3.58	26.64
S4	20	10	10			3.55	29.30
S4	20	11	9			3.51	32.56

S4	20	12	8			3.47	36.63
S4	20	13	7			3.43	41.86
S4	20	15	5			3.40	58.60
S4	20	20	0			3.36	#DIV/0!
S4	20	24	4	4.98	1.5	3.32	73.25
S5	20	-15	35	4.2	2.05	2.05	8.37
S5	20	-13.7	33.7			2.14	8.69
S5	20	-11.8	31.8			2.31	9.21
S5	20	-10	30	4.58	1.91	2.40	9.77
S5	20	-9.8	29.8			2.55	9.83
S5	20	-9.5	29.5			2.63	9.93
S5	20	-8.5	28.5			2.70	10.28
S5	20	-7	27			2.78	10.85
S5	20	-5	25			2.93	11.72
S5	20	-3	23			3.01	12.74
S5	20	-2	22			3.16	13.32
S5	20	0	20			3.24	14.65
S5	20	2	18			3.31	16.28
S5	20	3	17			3.39	17.24
S5	20	5	15			3.54	19.53
S5	20	7	13	5.5	1.52	3.62	22.54
S5	20	9	11			3.67	26.64
S5	20	10	10			3.73	29.30
S5	20	11	9			3.78	32.56
S5	20	12	8			3.84	36.63
S5	20	13	7			3.89	41.86
S5	20	15	5			3.95	58.60
S5	20	20	0			4.00	#DIV/0!
S5	20	24	4	6.25	1.54	4.06	73.25
S6	20	-15	35	5.15	2.84	1.81	8.37
S6	20	-13.7	33.7			1.89	8.69
S6	20	-11.8	31.8			2.05	9.21
S6	20	-10	30	6.02	2.82	2.13	9.77
S6	20	-9.8	29.8			2.27	9.83
S6	20	-9.5	29.5			2.34	9.93
S6	20	-8.5	28.5			2.40	10.28
S6	20	-7	27			2.47	10.85
S6	20	-5	25			2.61	11.72
S6	20	-3	23			2.67	12.74
S6	20	-2	22			2.81	13.32
S6	20	0	20			2.87	14.65
S6	20	2	18			2.94	16.28

S6	20	3	17			3.01	17.24
S6	20	5	15			3.14	19.53
S6	20	7	13			3.21	22.54
S6	20	9	11	7	2.18	3.27	26.64
S6	20	10	10			3.32	29.30
S6	20	11	9			3.38	32.56
S6	20	12	8			3.44	36.63
S6	20	13	7			3.50	41.86
S6	20	15	5			3.55	58.60
S6	20	20	0			3.61	#DIV/0!
S6	20	24	4	8.25	2.25	3.67	73.25
S7	20	-15	35	4.86	2.78	1.75	8.37
S7	20	-13.7	33.7			1.84	8.69
S7	20	-11.8	31.8			2.01	9.21
S7	20	-10	30	6.1	2.91	2.10	9.77
S7	20	-9.8	29.8			2.24	9.83
S7	20	-9.5	29.5			2.31	9.93
S7	20	-8.5	28.5			2.38	10.28
S7	20	-7	27			2.45	10.85
S7	20	-5	25			2.59	11.72
S7	20	-3	23			2.66	12.74
S7	20	-2	22			2.81	13.32
S7	20	0	20			2.88	14.65
S7	20	2	18			2.95	16.28
S7	20	3	17			3.02	17.24
S7	20	5	15			3.16	19.53
S7	20	7	13	7.5	2.32	3.23	22.54
S7	20	9	11			3.28	26.64
S7	20	10	10			3.33	29.30
S7	20	11	9			3.38	32.56
S7	20	12	8			3.43	36.63
S7	20	13	7			3.48	41.86
S7	20	15	5			3.53	58.60
S7	20	20	0			3.58	#DIV/0!
S7	20	24	4	7.8	2.15	3.63	73.25
T1	35	-20	55	3.83	1.82	2.10	5.60
T1	35	-19.8	54.8			2.18	5.62
T1	35	-18.8	53.8			2.25	5.72
T1	35	-16.7	51.7			2.32	5.96
T1	35	-15	50	4.54	1.9	2.39	6.16
T1	35	-13.7	48.7			2.39	6.32
T1	35	-11.8	46.8			2.39	6.58

T1	35	-10	45			2.39	6.84
T1	35	-9.8	44.8			2.39	6.88
T1	35	-9.5	44.5			2.40	6.92
T1	35	-8.5	43.5			2.40	7.08
T1	35	-7	42	5.3	2.21	2.40	7.33
T1	35	-5	40			2.47	7.70
T1	35	-3	38			2.63	8.11
T1	35	-2	37	6.11	2.26	2.70	8.32
T1	35	0	35			2.83	8.80
T1	35	2	33	6.75	2.28	2.96	9.33
T1	35	3	32			3.28	9.63
T1	35	5	30			3.92	10.27
T1	35	7	28	8.78	2.07	4.24	11.00
T1	35	9	26			4.41	11.85
T1	35	10	25	9.29	2.03	4.58	12.32
T1	35	11	24			4.72	12.83
T1	35	12	23	9.81	2.02	4.86	13.39
T1	35	13	22			5.05	14.00
T1	35	15	20	10.6	2.02	5.25	15.40
T1	35	20	15	11.99	2.01	5.97	20.53
T2	35	-20	55	5.48	2.97	1.85	5.60
T2	35	-19.8	54.8			1.94	5.62
T2	35	-18.8	53.8			2.03	5.72
T2	35	-16.7	51.7			2.13	5.96
T2	35	-15	50	6.86	3.09	2.22	6.16
T2	35	-13.7	48.7			2.24	6.32
T2	35	-11.8	46.8			2.25	6.58
T2	35	-10	45			2.27	6.84
T2	35	-9.8	44.8			2.30	6.88
T2	35	-9.5	44.5			2.32	6.92
T2	35	-8.5	43.5			2.34	7.08
T2	35	-7	42	8	3.4	2.35	7.33
T2	35	-5	40			2.50	7.70
T2	35	-3	38			2.80	8.11
T2	35	-2	37	9.9	3.35	2.96	8.32
T2	35	0	35			3.08	8.80
T2	35	2	33	10.55	3.3	3.20	9.33
T2	35	3	32			3.56	9.63
T2	35	5	30			4.28	10.27
T2	35	7	28	14.97	3.23	4.63	11.00
T2	35	9	26			4.79	11.85
T2	35	10	25	15.87	3.21	4.94	12.32

T2	35	11	24			5.24	12.83
T2	35	12	23	16.62	3	5.54	13.39
T2	35	13	22			5.54	14.00
T2	35	15	20	17.7	3.19	5.55	15.40
T2	35	20	15	20.01	3.17	6.31	20.53
T3	35	-20	55	6.18	3.5	1.77	5.60
T3	35	-19.8	54.8			1.86	5.62
T3	35	-18.8	53.8			1.96	5.72
T3	35	-16.7	51.7			2.06	5.96
T3	35	-15	50	7.94	3.69	2.15	6.16
T3	35	-13.7	48.7			2.17	6.32
T3	35	-11.8	46.8			2.19	6.58
T3	35	-10	45			2.20	6.84
T3	35	-9.8	44.8			2.24	6.88
T3	35	-9.5	44.5			2.25	6.92
T3	35	-8.5	43.5			2.27	7.08
T3	35	-7	42	9.37	4.1	2.29	7.33
T3	35	-5	40			2.39	7.70
T3	35	-3	38			2.60	8.11
T3	35	-2	37	10.93	4.04	2.71	8.32
T3	35	0	35			2.80	8.80
T3	35	2	33	11.56	3.98	2.90	9.33
T3	35	3	32			3.26	9.63
T3	35	5	30			3.98	10.27
T3	35	7	28	17.08	3.94	4.34	11.00
T3	35	9	26			4.44	11.85
T3	35	10	25	17.93	3.94	4.55	12.32
T3	35	11	24			4.68	12.83
T3	35	12	23	18.96	3.95	4.80	13.39
T3	35	13	22			4.92	14.00
T3	35	15	20	20.09	3.98	5.05	15.40
T3	35	20	15	21.87	3.75	5.83	20.53
WB1	20	-15	35	2.5	2.5	1.00	8.37
WB1	20	-13.7	33.7			1.04	8.69
WB1	20	-11.8	31.8			1.07	9.21
WB1	20	-10	30			1.11	9.77
WB1	20	-9.8	29.8			1.18	9.83
WB1	20	-9.5	29.5			1.21	9.93
WB1	20	-8.5	28.5			1.25	10.28
WB1	20	-7	27	3.2	2.5	1.28	10.85
WB1	20	-5	25			1.30	11.72
WB1	20	-3	23			1.33	12.74

WB1	20	-2	22			1.36	13.32
WB1	20	0	20			1.39	14.65
WB1	20	2	18	3.5	2.5	1.40	16.28
WB1	20	3	17			1.52	17.24
WB1	20	5	15			1.76	19.53
WB1	20	7	13	4.7	2.5	1.88	22.54

Appendix G – Heat Pump Sensitivity Data

Table 22. Overall heat pump sensitivity

ID Tag	Start Source Temperature (°C)	End Source Temperature (°C)	ΔT (°C)	Start COP	End COP	ΔCOP	ΔCOP/ΔT
D1	-19.8	15	34.8	3.26	4.39	1.13	0.032
D2	-19.8	15	34.8	3.74	4.95	1.21	0.035
D3	-19.8	15	34.8	3.25	4.95	1.7	0.049
D4	-19.8	15	34.8	4.1	4.97	0.87	0.025
D5	-19.8	15	34.8	3.33	4.8	1.47	0.042
D6	-19.8	15	34.8	3.34	4.68	1.34	0.039
D7	-19.8	15	34.8	3.83	4.61	0.78	0.022
K1	-3	7	10	3.09	4.06	0.97	0.097
K2	-3	7	10	2.93	4.22	1.29	0.129
K3	-3	7	10	2.81	3.92	1.11	0.111
K4	-3	7	10	2.88	3.98	1.1	0.11
K5	-3	7	10	2.85	4.06	1.21	0.121
S1	-15	24	39	2.1	3.67	1.57	0.04
S2	-15	24	39	1.78	3.39	1.61	0.041
S3	-15	24	39	2.21	4.03	1.82	0.047
S4	-15	24	39	2.15	3.32	1.17	0.03
S5	-15	24	39	2.05	4.06	2.01	0.052
S6	-15	24	39	1.81	3.67	1.86	0.048
S7	-15	24	39	1.75	3.63	1.88	0.048
T1	-20	20	40	2.1	5.97	3.87	0.097
T2	-20	20	40	1.85	6.31	4.46	0.112
T3	-20	20	40	1.77	5.83	4.06	0.102
WB1	-15	7	22	1	1.88	0.88	0.04

Table 23. Heat pump sensitivity per temperature range

ID Tag	Start Source Temperature (°C)	End Source Temperature (°C)	ΔTs (°C)	Start COP	End COP	ΔCOP	ΔCOP/ΔTs	Temperature Range
D1	-20	-5	14.8	3.26	3.59	0.33	0.02	Low
D2	-20	-5	14.8	3.74	4.09	0.35	0.02	Low
D3	-20	-5	14.8	3.25	3.48	0.23	0.02	Low
D4	-20	-5	14.8	4.1	3.96	-0.14	-0	Low
D5	-20	-5	14.8	3.33	3.5	0.17	0.01	Low
D6	-20	-5	14.8	3.34	3.5	0.16	0.01	Low
D7	-20	-5	14.8	3.83	3.7	-0.13	-0	Low
S1	-15	-5	10	2.1	3.02	0.92	0.09	Low
S2	-15	-5	10	1.78	2.86	1.08	0.11	Low
S3	-15	-5	10	2.21	2.96	0.75	0.08	Low
S4	-15	-5	10	2.15	2.94	0.79	0.08	Low
S5	-15	-5	10	2.05	2.93	0.88	0.09	Low
S6	-15	-5	10	1.81	2.61	0.8	0.08	Low
S7	-15	-5	10	1.75	2.59	0.84	0.08	Low
T1	-20	-5	15	2.1	2.47	0.37	0.02	Low
T2	-20	-5	15	1.85	2.5	0.65	0.04	Low
T3	-20	-5	15	1.77	2.39	0.62	0.04	Low
WB1	-15	-5	10	1	1.3	0.3	0.03	Low
D1	-3	7	10	3.66	4.03	0.37	0.04	Medium
D2	-3	7	10	4.16	4.59	0.43	0.04	Medium
D3	-3	7	10	3.56	4.09	0.53	0.05	Medium
D4	-3	7	10	3.99	4.43	0.44	0.04	Medium
D5	-3	7	10	3.58	4.06	0.48	0.05	Medium
D6	-3	7	10	3.54	4.01	0.47	0.05	Medium
D7	-3	7	10	3.75	4.13	0.38	0.04	Medium
K1	-3	7	10	3.09	4.06	0.97	0.1	Medium
K2	-3	7	10	2.93	4.22	1.29	0.13	Medium
K3	-3	7	10	2.81	3.92	1.11	0.11	Medium
K4	-3	7	10	2.88	3.98	1.1	0.11	Medium
K5	-3	7	10	2.85	4.06	1.21	0.12	Medium
S1	-3	7	10	3.08	3.63	0.55	0.06	Medium
S2	-3	7	10	2.92	3.45	0.53	0.05	Medium
S3	-3	7	10	3.04	3.67	0.63	0.06	Medium
S4	-3	7	10	3.02	3.62	0.6	0.06	Medium
S5	-3	7	10	3.01	3.62	0.61	0.06	Medium
S6	-3	7	10	2.67	3.21	0.54	0.05	Medium
S7	-3	7	10	2.66	3.23	0.57	0.06	Medium
T1	-3	7	10	2.63	4.24	1.61	0.16	Medium

T2	-3	7	10	2.8	4.63	1.83	0.18	Medium
T3	-3	7	10	2.6	4.34	1.74	0.17	Medium
WB1	-3	7	10	1	1.88	0.88	0.09	Medium
D1	9	15	6	4.11	4.39	0.28	0.05	High
D2	9	15	6	4.68	4.95	0.27	0.05	High
D3	9	15	6	4.22	4.95	0.73	0.12	High
D4	9	15	6	4.55	4.97	0.42	0.07	High
D5	9	15	6	4.2	4.8	0.6	0.1	High
D6	9	15	6	4.15	4.68	0.53	0.09	High
D7	9	15	6	4.21	4.61	0.4	0.07	High
S1	9	24	15	3.63	3.67	0.04	0	High
S2	9	24	15	3.44	3.39	-0.05	-0	High
S3	9	24	15	3.71	4.03	0.32	0.02	High
S4	9	24	15	3.58	3.32	-0.26	-0	High
S5	9	24	15	3.67	4.06	0.39	0.03	High
S6	9	24	15	3.27	3.67	0.4	0.03	High
S7	9	24	15	3.28	3.63	0.35	0.02	High
T1	9	20	11	4.41	5.97	1.56	0.14	High
T2	9	20	11	4.79	6.31	1.52	0.14	High
T3	9	20	11	4.44	5.83	1.39	0.13	High

Appendix H – Sample Heat Pump COP Calculations

Using Indoor Air to Alter Source Temperature

$$T_{source} = \frac{(T_O \times (Q_E - Q_B) + T_I \times Q_B)}{Q_E}$$

$$T_{source} = \frac{2 \times (1.68 - 0.16) + 20 \times 0.16)}{1.68}$$

$$T_{source} = \frac{3.04 + 3.2}{1.68}$$

$$T_{source} = \frac{6.24}{1.68}$$

$$T_{source} = 3.71$$

$$COP = 0.0022{T_{source}}^2 + 0.1201T_{source} + 3.3424$$

$$COP = 0.0022(3.71)^2 + 0.1201(3.71) + 3.3424$$

$$COP = 0.03028102 + 0.445571 + 3.3424$$

$$COP = 3.82$$

Using Indoor Air with Heat Recovery to Alter Source Temperature

$$T_{source} = \frac{(T_O \times (Q_E - Q_B) + ((T_I - T_O) \times HR_{Eff} + T_O) \times Q_B)}{Q_E}$$

$$T_{source} = \frac{2 \times (1.68 - 0.16) + \big((20 - 2) \times 0.83 + 2\big) \times 0.16}{1.68}$$

$$T_{source} = \frac{3.04 + 2.7104}{1.68}$$

$$T_{source} = \frac{5.7504}{1.68}$$

$$T_{source} = 3.42$$

$$COP = 0.0022{T_{source}}^2 + 0.1201T_{source} + 3.3424$$

$$COP = 0.0022(3.42)^2 + 0.1201(3.42) + 3.3424$$

$$COP = 0.02573208 + 0.410742 + 3.3424$$

$$COP = 3.78$$

Using Indoor Air with Waste Heat from Compressor to Alter Source Temperature

$$T_{source} = \frac{(T_O \times (Q_E - Q_B) + T_I \times Q_B)}{Q_E} + \frac{E_C}{(Q_E \times \rho_{Air} \times C_{Air})}$$

$$T_{source} = \frac{(2 \times (1.68 - 0.16) + 20 \times 0.16)}{1.68} + \frac{590}{(1.68 \times 1.2 \times 1000)}$$

$$T_{source} = 3.71 + \frac{590}{2016}$$

$$T_{source} = 3.714285714 + 0.29265873$$

$$T_{source} = 4.01$$

$$COP = 0.0022{T_{source}}^2 + 0.1201T_{source} + 3.3424$$

$$COP = 0.0022(4.01)^2 + 0.1201(4.01) + 3.3424$$

$$COP = 0.03537622 + 0.481601 + 3.3424$$

$$COP = 3.86$$

Using Indoor Air with Heat Recovery and Waste Heat from Compressor to Alter Source Temperature

$$T_{source} = \frac{(T_O \times (Q_E - Q_B) + ((T_I - T_O) \times HR_{Eff} + T_O) \times Q_B)}{Q_E} + \frac{E_C}{(Q_E \times \rho_{Air} \times C_{Air})}$$

$$T_{source} = \frac{(2 \times (1.68 - 0.16) + ((20 - 2) \times 0.83 + 2) \times 0.16)}{1.68} + \frac{590}{(1.68 \times 1.2 \times 1000)}$$

$$T_{source} = 3.422857143 + 0.29265873$$

$$T_{source} = 3.72$$

$$COP = 0.0022{T_{source}}^2 + 0.1201T_{source} + 3.3424$$

$$COP = 0.0022(3.72)^2 + 0.1201(3.72) + 3.3424$$

$$COP = 0.03044448 + 0.446772 + 3.3424$$

$$COP = 3.82$$