Department of Mechanical and Aerospace Engineering

5^{th} Generation District Heating and Cooling Retrofit a Case study: The University of Strathclyde

Author: Grant Ewing

Supervisor: Dr Nick Kelly

A thesis submitted in partial fulfilment for the requirement of the degree
Master of Science
Sustainable Engineering: Renewable Energy Systems and the Environment
2020

Abstract

District heating currently serves 1% of the heating demand in Scotland and with the recent Formations of the Governments heat network bill gives it the potential of serving 10%. The 5th generation of district heating cooling network (5GDHCN) systems utilises far lower supply temperature than the previous generations of the technology, thus vastly increasing the feasibility to utilising heat pumps as the main technology to upgrade heat from local sources. More commonly than not the heat pumps are powered by electricity thus can take advantage of the decreasing carbon intensity of the electricity grid in Scotland and in turn contributing to decarbonising heat which is lagging far behind electricity. There is already a considerable amount of district heat networks (DHN) in Scotland and this thesis investigates the feasibility of upgrading the current DHN at the university of Strathclyde to a 5th generation system.

Analysis of the heating demand on the current network was analysed and the resources that could contribute to a 5th generation system were assessed. Enormous potential was for the river Clyde to be a potential source for the heat pump, however, a key part of a 5GDHCN is the seasonal storage and there was found to be and difficulties were found in locating space for this storage, which is common for high density urban areas, such as the University of Strathclyde which is located in the city centre of Glasgow.

As the 5GDHCN utilises lower supply temperature the supply temperatures to the heat emitter will be reduced. A section of the Royal College building was modelled, and packages of passive retrofits were added to reduce the energy demand thus allowing for lower heating capacity in the zones modelled. It was found that external and internal walls as well as floor and ceiling would need to be insulated for 55^{o}C to be utilised. Triple glazing was found not to be necessary.

The main results show that district heating networks this size in dense urban areas would be difficult due to lack of space for storage. Also, the economic case for the retrofit makes it difficult to justify from economic standpoint. Nonetheless is feasible for buildings as old as the Royal College

Acknowledgements

Firstly, I would like to thank to Dr Nick Kelly for supervising this thesis, for taking the time for weekly meetings that helped shaped the thesis and improved initial methodologies.

I would also like to thank Jon Hands who helped greatly with the installation of the ESP-r software as well as my fellow students who used ESP-r for their project for their help with the software and to David Charles from the O and M team at the university who provided the information on the current system and was on hand to help with enquires about the campus itself.

Lastly, I would like to thank my partner Alicia for her constant support throughout the thesis.

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1 Introduction

1.1 Overview

District heating is a means to distribute heat to multiple buildings from one centralised source that was initially created to take advantage of greater efficiencies of larger systems to save energy. The District Heating Network (DHN) at the University of Strathclyde would currently be considered a 3rd generation system with the main production of energy coming from a gas fired CHP boiler. This thesis investigates the feasibility of upgrading this DHN to a 5th Generation District Heating and Cooling Network (5GDHCN). The main justification for this study is due to the massive reductions in energy consumption thus carbon emissions in heating that 5th generation DHN can achieve in comparison to its predecessors and this falls in line with government policy. Due to the UK climate this thesis will focus only on the heating aspect of a 5GDHCN.

The UK government has set a target for net zero carbon emissions by 2050, whilst the Scottish government aims to achieve this goal 5 years earlier in 2045. Great strides have been made in the UK to decarbonise the electricity grid and in particular Scotland, with the use of coal being dramatically cut over the last 10 years from 100TWh per year in 2009 to 13TWh per year in 2018 with renewable energy increasing from 25TWh in 2009 to 112TWh to 2018 (Evans, 2019). Additionally, in 2018 renewable energy accounted for 74.8% of electricity demand in Scotland and is on course to achieve the goal of 100% by 2020 (Scottish Government, 2019). However, the same cannot be said for heating where 85% of space heating in the UK is being met by natural gas boilers. As the grid further decarbonises the environmental benefits of CHP decreases as electricity become less carbon intensive than gas.

To decarbonise heating within the UK there is a need to reduce the amount of heat needed, improve the way in which heat is supplied to the end user and switch to lower carbon and renewable heat generation; these three aspects will be covered in this thesis. The UK current building stock both residential and commercial currently lags behind that of its European counterparts. There will need to be mass amounts of retrofitting throughout the UK in all buildings, as the majority of these buildings will still be in use in 2050, 80% for residential in particular (Ben and Steemers, 2020). DHN can also be seen as a more secure way to provide the heating demand as they tend to make use of local energy sources that will reduce the imports currently needed for the natural gas infrastructure in the UK. One of the more promising ways to cut the carbon emissions is to electrify the heating demand, since as previously mentioned the electricity grid is much less carbon intense in comparison to natural gas and is only going to improve. Heat pumps are used to transfer and upgrade heat from a source whether that be air, ground or water and pump it to a building where it can be used for space heating and domestic hot water (DHW).

5th Generation District Heating and Cooling (5GDHC) reduce the supply temperature from usual DHN temperature of 100-90 ^{o}C to near ambient temperatures 35-25 ^{o}C. This reduction in temperature dramatically reduces the energy required to produce heat and improves the viability of technologies that can be incorporated in the system as well as improving the utilisation of waste heat that has been done since the 4th generation. Although 5GDHC systems create ample amount of opportunities to incorporate what would be otherwise waste heat the 5GDHC at the University of Strathclyde will be restricted due to the DHN already in place as the pipework already installed will be used to avoid digging up the road to relay pipes and reduce costs.

The UK government has incentivised the uptake of heat-pumps through the RHI scheme (see section 2.5.1) however the uptake has not been plentiful with only 60,000 heat pumps under RHI, at the current rate of installs it would take over 1520 years for the installations to reach 9 million which is estimated will be needed to fully electrify UK heating (Page, 2020). However, due to economies of scale they become more viable economically, especially those that operate at ambient temperature as the temperature difference and between the source and output decreases the efficiency increases. 5GDHC systems have been recorded to have coefficient of performance (COP) of more than 10, thus for every kW of electrical energy consumed the output is 10kW of heating.

1.2 Aims

The aim of the project is to assess the viability of retrofitting a DHN so that it can operate as a 5GDHC network by using the case study of the DHN that is in operation at the University of Strathclyde. The specific aims are;

1. Analyse the demand on the current network through the operation reports provided by Vital Energi.

2. Assess the feasibility of local energy resources around the campus and evaluate if they would be able to match the demand.

3. Through building simulation evaluate retrofits that would be needed to make low temperatures heating feasible.

4. Calculate the impact of the sizes of the heating systems in the rooms for utilising the low temperature heat with retrofits.

5. Economic evaluation of the retrofits from calculations of payback period and net present value.

1.3 Methodology

Analysis of the demand that the current DHN supplies will be done through the use of real data that was provided to the university by Vital Energies the company that was contacted to construct and maintain DHN. The energy resources in near vicinity of the current DHN network will be mapped out on Google Earth Pro and evaluated through methods approved by past literature. A section of one of the buildings that is connected to the DHN will be modelled in ESP-r software, the base model will be calibrated against the data provided, the model will then be subject to multiple retrofits packages. Initially each model will be simulated with an abundant amount of heating capacity, gauge the correct capacity the model requires. The correct capacity will then be implemented into the model and simulation carried out to calculate the annual energy delivered of the model and the thermal comfort that is achieved with the heating capacity. Finally, the retrofits implemented to the model will then be economically assessed.

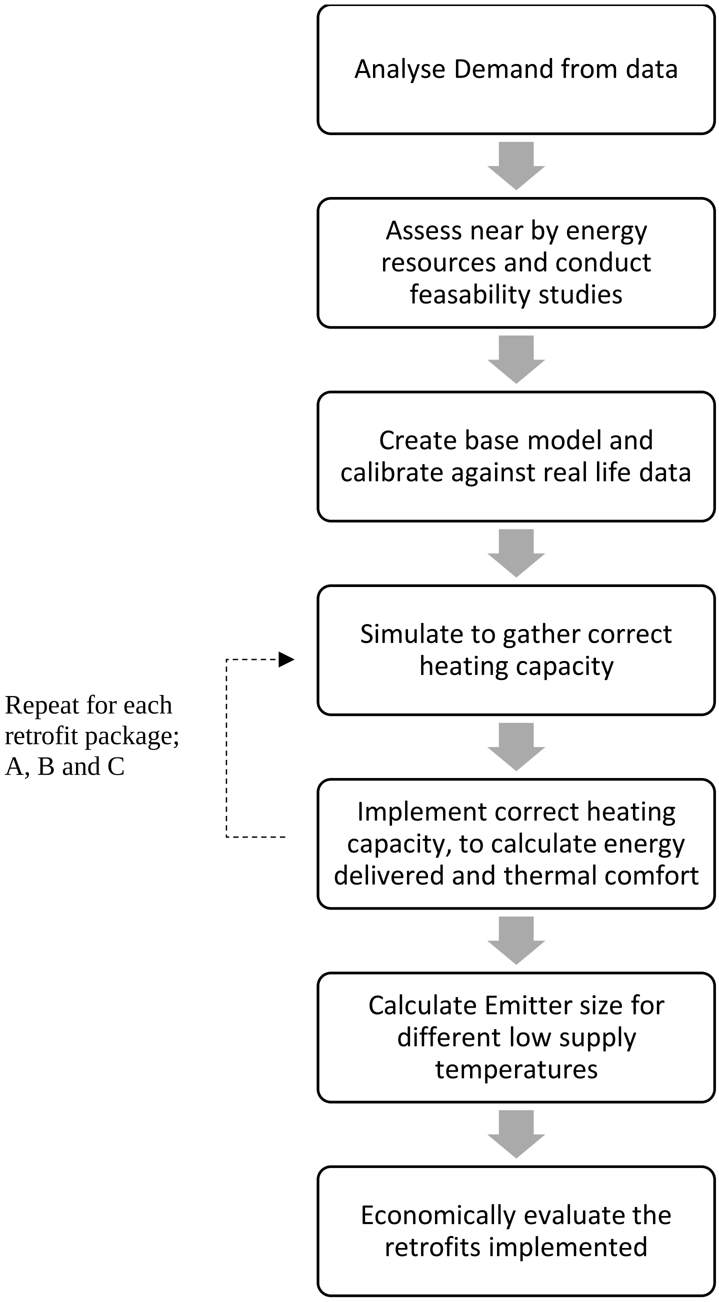

Figure 1-1: Methodology to thesis.

1.4 Structure

Chapter 2 presents a critical literature relevant to 5GDHC and the problems that can arise from implementing this system in comparison to traditional systems. Starting with a thorough explanation of exactly what DHN are and their advantages and the progression advancement of district heating. Heat pumps are then discussed as this technology is used in 5GDHC and the different sources can be used will be examined. The various forms of energy storage are then discussed as this is pivotal to the sustainable aspect of a 5GDHN. Advancements in heat emitters that allow lower supply temperatures to be used. Legislation that supports development of 5GDHN is also discussed and so is legionella because it becomes a critical issue when using lower temperatures.

In Chapter 3 the characteristics of the current DHN at the university is discussed going into detail on the specifications of the systems. The demand that is on the systems is broken down per building from information monthly reports by Vital Energi.

In Chapter 4 the potential energy sources that could be utilized by the 5GDHCN are analysed with a simplistic feasibility study done for each resource and their ability to match the demand of the DHN.

Chapter 5 describes the characteristics of the model that will be used to assess the effectiveness of the retrofits thus the size of the potential emitter describing the materials used in the model and the materials used for the retrofits.

The main body of results is presented in Chapter 6 where each model is simulated to gather the energy delivered to the room, the minimum heating capacity for each room to provide thermal comfort is analysed and from that the size of emitter for varying low temperatures is discussed.

Chapter 7 presents the economic analysis of the retrofits that were described in Chapter 5 and simulated in Chapter 6

Chapter 8 presents the key finding to the project as well as its limitation and future work to be conducted in the subject area.

2 Literature Review

2.1 District Heating and Cooling

2.1.1 Overview

District heating is a means to distribute thermal energy, typically used a centralised generation system that is not connected to the gas grid. These heating networks can range from a few households to city wide systems that can be seen in Copenhagen. The key appeal of a district heating system is that the larger centralised systems have a higher efficiency than, for example a gas boiler for an individual household. Furthermore, there is also the key factor that natural resources for such as geothermal, can be exploited by such DHNs as the capital cost becomes more viable at the network scale. From the centralised energy system, the heat is transferred to a distribution medium that transports the heat to the building connected to the DHN through underground pipes. There are now several types of classifications of DHN:

- Heat Source; the main heat generation that accounts for the majority of the heat demand at the energy centre for the network, the sources of energy production have changed with typically being oil and gas boilers then moved the CHP plants and HP. In recent systems

- Distribution medium: There are three options for distribution medium; steam water and air

- Heat Type; some DHN are used solely used to provide space heating however can also be used for hot water and more recently cooling

- Open or closed loop; Open loop systems extract the thermal source to be utilised at the heat pump and a closed loop system uses a carrier medium that exchanges thermal energy at the source.

- Number of pipelines; DHN have been designed with 1 to 4 pipes. a one pipe system; is an open loop system operating at ambient temperature, two pipeline system with supply and return, a triple pipe system where the supply for space heating and DHW are separate this can lead to decreases in heat-pump size but come with the additional cost of the extra pipe and construction work needed

(Arabkoohsar and Alsagri, 2020) and a four-pipeline system with cooling and heating having both a supply and return pipelines.

- Energy and Medium Directionality DHN the energy and medium direction can be both unidirectional and bidirectional.

- Topology; DHN can be split into three topology types; Ring, Radial, and Meshed which is a mixture of both ring and radial.

2.1.2 District Heating and Cooling Development

District heating has constantly evolved with the advancement of technology regarding energy systems. There is evidence that the first DHN was around in the 14^{th} century (Lake, Rezaie and Beyerlein, 2017), but it was in the late 19^{th} century when they were first commercially introduced (von Rhein *et al.*, 2019). The district systems that were used in the late 19^{th} century would utilise coal in steam boilers as the main energy source and use steam as the carrier medium through steel pipes inside concrete ducts. These systems are now referred to as 1^{st} generation district heating. To reduce system losses the carrier medium in DHN was changed from steam to hot water around the 1930's this is also when CHPs started to be used were started to be used. These changes brought the 2^{nd} generation of district heating. 3^{rd} generation districted heating reduced the supply temperatures of the hot water were reduced to between 90^{o}C and 60^{o}C were used to of the system and this was achievable due to the improvements in building fabrics in the 1980's. The reduction in the supply temperature also allowed for the adoption of plastic jacket pipes. CHPs were mainly used for this generation however different fuels like biomass were starting to be used. The 4th generation of district heating saw the supply temperature drop down again, to around 55^{o}C and is also referred to as low temperature district heating (LTDH). It is at this stage that district heating starts to integrate with renewable energy technology to create smart thermal grids. Smart thermal grids must include the low-energy space heating, cooling and DHW, utilising low carbon heating such as waste heat and renewable heat from solar hot water collectors (Lund *et al.*, 2014). 5th generations again focus on the decrease of the supply temperature to below 30^{o}C, which may be referred to as ultra-low temperature district heating (ULTDH). A major difference is that heat pumps are used to upgrade heat sources rather that energy production technologies such as CHPs. An overview of the progression of District heating can be seen on Figure 2-1. District cooling has 3 known generations however, they are not as prevalent in the built environment due their main utilisation being in the commercial retail sector for fridges in the retail sector; first generation contained centralised condensers and decentralised evaporators, then evolved to 2nd generation after the creation of centrifugal chiller and the final generation created after the banning of the majority of refrigerants (von Rhein *et al.*, 2019).

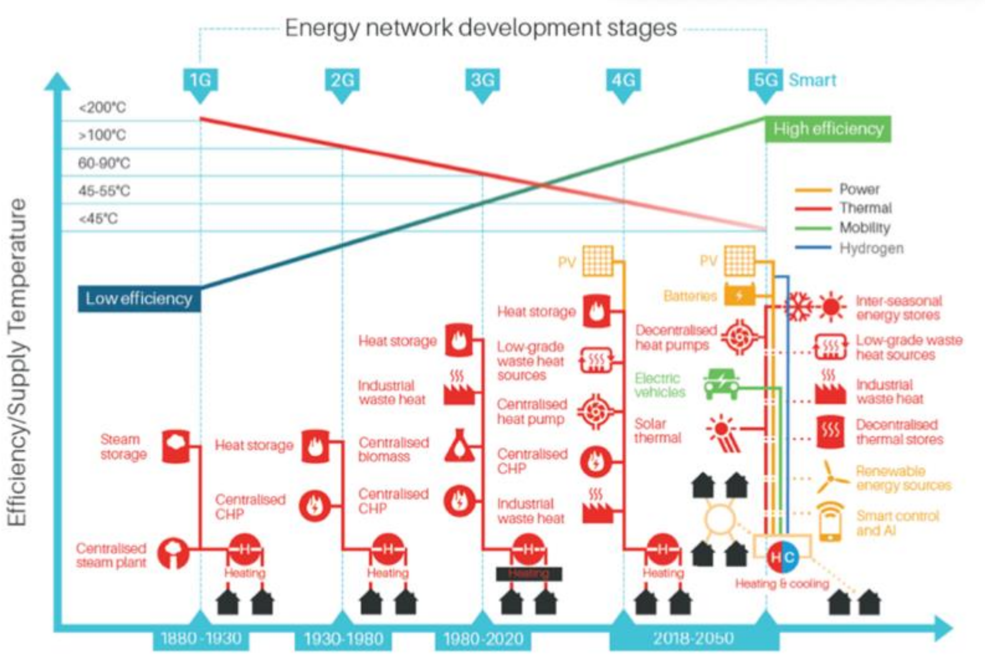

Figure 2-1 Overview of the generation progression of DHN (Revesz *et al.*, 2020)

2.1.3 5th Generation District Heating and Cooling

As mentioned in the previous section 5GDH builds on the smart thermal network that was created in the 4th generation, however, further reduces the supply temperature and importantly differentiates from the previous generations as it utilises heat- pump and strays any from energy production technologies such as CHP's. This is due to the ever-expanding use of renewable energy technologies that have seen a dramatic increase that has seen the United Kingdom and particularly Scotland have extremely clean electrical grid that is on course to be 100% renewable by the end of 2020 , thus utilising heat pumps will create renewable heating (Scottish Government, 2019). There is a slight confusion over the true definition and distinction between 4th and 5th generation due to lack of time between the generation and there has been several different definitions for example a definition has been provided in a recent project review 5GDHCN in Europe (Buffa *et al.*, 2019);

"A 5GDHC network is a thermal energy supply grid that uses water or brine as a carrier medium and hybrid substation with Water Source Heat Pumps (WSHP). It operates at temperatures so close to the ground that it is not suitable for direct heating purpose. The low temperature of the carrier medium gives the opportunity to exploit directly industrial and urban excess heat and the use of renewable heat sources at low thermal exergy content. The possibility to reverse the operation of the customer substations permits to cover simultaneously and with the same pipelines both the heating and cooling demands of different buildings. Through hybrid substations, 5GDHC technology enhances sector coupling of thermal, electrical and gas grids in a decentralised smart energy system."

However, this definition again has problems as it specifies that a 5th generation must utilise a WSHP and although this is a perfect viable option there are many 5GDHC systems that use different sources as presented in the same journal. The temperatures that a 5GDHC network uses is only described as low enough to make use of waste heat which can be done with 4th generation heating thus a concise definition of the 5GDHC system is yet to be defined in academia. Supply temperatures have been widely defined as 15-25oC (Revesz *et al.*, 2020). A ring diagram of a 5GDHCN can be seen below in Figure 2-2.

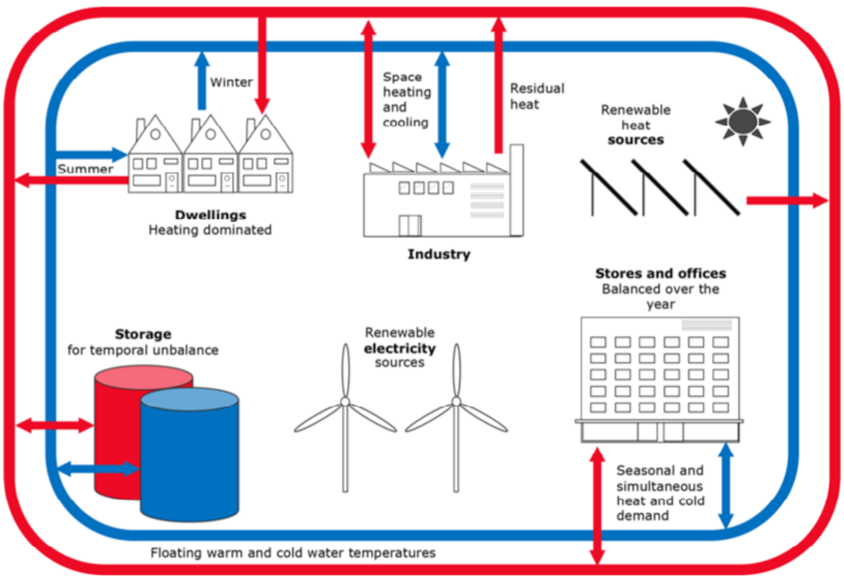

Figure 2-2: Ring diagram encapsulating major systems involved in 5GDHCN (Boesten *et al.*, 2019).

2.2 Heat Pumps

Heat pumps are one of the main technologies that are used for renewable heating, heat pumps do use electrical energy therefore it is dependant of the source of that electronic energy whether or not the heat-pump is renewable. In the case of Scotland where Strathclyde University is located renewable energy provided 74.6% of gross electricity in 2018 and is expected to be 100% in 2020 (Scottish Government, 2019).

2.2.1 Mechanics

The operation of a heat pumps is shown in Figure 2-3, the system is connected to a thermal source that can be air, water or ground and the system absorbs heat from the source which is used to evaporate the fluid inside the heat pump system. The then heated up fluid is processed in the condenser where the pressure is increased. It is at this stage where heat is then transferred to the carrier medium of the DHN, the fluid in the heat pump now cooled from the heat exchange is further reduced after going through the expansion valve and the cycle begins again.

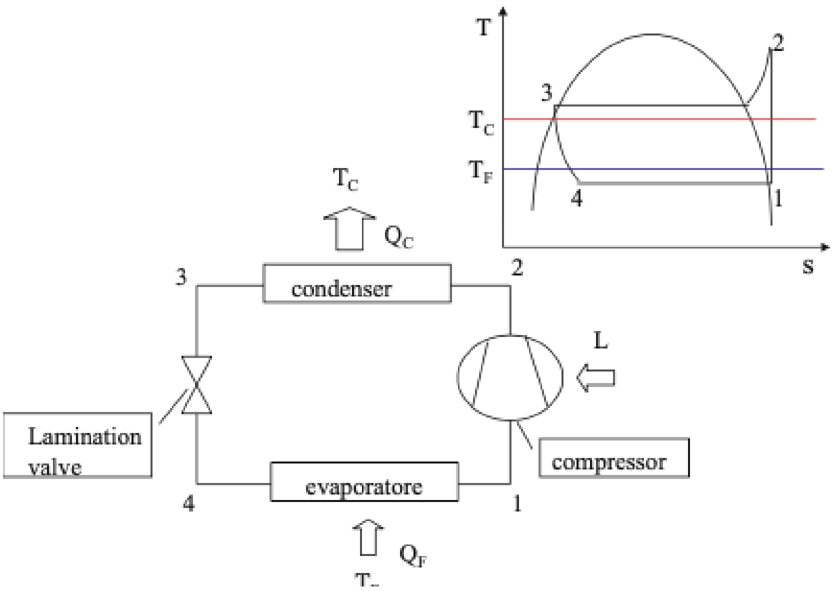

Figure 2-3: Heat pump schematic paid with the an ideal T-s diagram in the top left. (Grassi, 2018).

Heat pumps can also operate in winter and summer mode to provide cooling therefore another energy system is not needed to provide the cooling in 5GDHCN. The one modification that is required is a four-way reversion valve at the compressor.

2.2.2 Performance

The efficiency or COP of a heat pump is determined by how much thermal energy output to the amount of electrical energy shown in Eq 1.

$$COP = \frac{Q_c}{L} = \frac{1}{1 - \frac{T_f}{T_c}\left(1 - \frac{T_c S_g}{|Q_c|}\right)} \quad (1)$$

Qc being the thermal energy output of the heat pump, L being the energy into the compressor, T_f, being the temperature at the thermal source that feeds into the evaporator T_c the temperature at the condenser and S_g represents the irreversibility's that take place during the process. The COP for heat pumps in the UK has been found to maintain a COP of between 2 and 3 throughout the year. Another term that is used to describe the performance of a heat pump is seasonal coefficient of performance (SCOP) this describes the average COP for the heating season. SCOP for 5GDHCN ranges from 3 to 6 (Buffa *et al.*, 2019). Values as high as 7.2 and 5.8 for COP and SCOP respectively are recoded for the 5GDHCN installed in the ETH Zurich university campus, this is achieved through the utilisation of the ATES (see section 2.3) and recycling waste heat from air conditioning refrigeration which is available to be utilised at the DHN operates with a 24$_o$C supply temperature. In terms of Eq 2-1 the COP and SCOP are so high in the heat pumps at the ETH Zurich campus due to a low Q_c and T_c being required and the T_f being increased due to thermal storage and the utilisation of waste heat.

2.2.3 Resources

As previously mentioned, a heat pump requires a thermal resource. There are three main categories of this; air, ground and water. The three sources have their advantages and disadvantages which can be seen in Table 2-1. It should be noted that there are sub-sections for each resource type, for example the GSHP are more commonly dug tens or even hundreds of meters underground to take advantage of a more stable heat source however, there are GSHP that operate at near surface levels 1 to 5m deep to the pipes cover a long surface area to increase the amount of heat they absorbed in the district heat system in Sohnius-Weide German the pipes are laid 1.5 meters deep and is 450 meters long (Energie Agentur NRW, 2017) . Water Source heat pumps come in different variations due to the body of water that it can be connected to e.g. lake, river, sea and ground water. Ground water systems require digging into the ground to find water trapped between rocks this can occur naturally or in some cases the water is located in old mine shafts, this is utilised in a DHN in Heerlen in the Netherlands where 3 different mines are used for a different temperature heat dumps (Verhoeven *et al.*, 2014). River source heat pump are more known due the successful implementation in the Drammen DHN in Norway that is powered off a hydroelectric dam and there is also one currently under-construction that is located in the Clyde river in Glasgow.

Resource	Pros	Cons
Air	• Easy to install • Least expensive option	• Less efficient due to season variation of ambient temperature • Increased maintenance due to freezing • Requires most plant room space
Ground	• More stable temperature year round • Less maintenance, heat pump protected from element underground • Reduced noise	• More upfront cost due to the need for drilling • Large area required for boreholes
Water	• Even more stable than ground • Flow in rivers mean source is constantly changing therefore difficult to deplete	• Most complex system to plan and implement • Most expensive system

Table 2-1: Different sources for heat pumps with their respective advantages and disadvantages.

2.3 Energy Storage

Although 5GDHC is a MES and there should be consideration for technologies such as electric vehicles associated with the buildings connected to the DHN, energy storage mostly focuses around thermal energy storage (TES). TES is an established technology however, its research has become more prominent due to the decarbonisation and electrification of heat as this is having the potential to be an instrumental part in demand side management. TES comes in many forms with the classifications presented in Figure 2-4. Most TES systems are sensible however research is being conducted into latent and chemical TES that are at different levels of maturity. All types of TES have the ability to shift demand however they also have drawback such as the space required which obviously increases in relation to how long you want to store the energy. There is also a high capital cost that varies from system type and size this is compounded by a lack of supportive legislation. TES systems also suffer from losses that increase with time thus greatly effect seasonal storage.

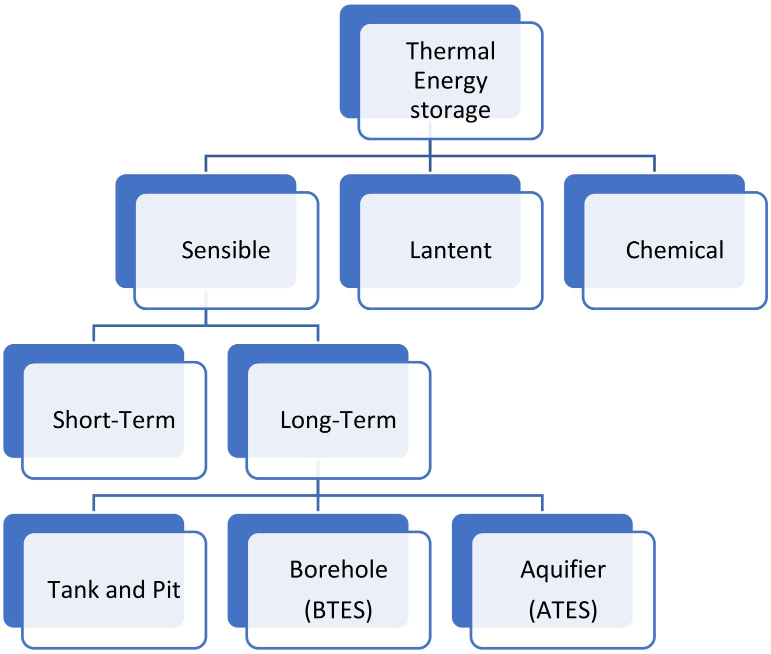

Figure 2-4: TES classification (Guelpa and Verda, 2019).

2.3.1 Short-Term TES

Daily storage can also play a key part in 5GDHCN as it allows systems to take advantage of daily electricity price fluctuations increasing the financial feasibility of the system (Guelpa and Verda, 2019). Daily storage is the most common type of storage found in DHN as they require the least space. A study done on DHN in the 5 Nordic countries found that the average size of the storages is $6m^3/TJ$ (Gadd and Werner, 2015) these storage systems are usually water tanks thus require space of between 10 and $100m^2$.

2.3.2 Long-Term TES

A key aspect of most 5GDHC systems that are already in operation is the inclusion of seasonal TES, seasonal or long-term storage is defined as storage that is kept for at least 3 months or longer. Seasonal TES for individual properties were found to be inefficient as the storage was found to always exceed the size of the building (Allison *et al.*, 2018). However, Seasonal TES becomes more viable in a 5GDHCN due to the economies of scale and more importantly due to the lowered supply temperature the storage temperature can also be lowered from traditional standards. This creates a massive scope for load shifting which would in turn vastly increase the feasibility of technologies such as solar collectors in locations such as Glasgow due to their peak output coinciding with lowest heat demand. Seasonal TES also creates additional incentive to utilise waste heat from source such as data centres and industrial processes as this resource is likely to be there year-round, thus can be stored for when most needed. Correct implementation of Long-Term TES in DHN can also lead to flexibility being high enough such that the further buildings can be connected to the system without any additional energy production required (Guelpa, Sciacovelli and Verda, 2019). Aquifers as previously mentioned are rocks that have ground water trapped in them thus their utilisation is limited to the restructure's underneath or close to the DHN. ATES has enormous potential as to store heat where it is geologically available it is a relatively new technology that is based around a GWHP (Todorov *et al.*, 2020). However, the system have an enormous capital cost and not only do they require the geological requirements but they also require open spaces for the drilling to take place that can be rare in large urban cities due to the planning and construction of the drilling to 100m deep and more planning required. ATES tend to be the most expensive type of TES . Borehole TES (BTES) uses an assembly of U-pipes these again like ATES have enormous potential to store heat however again have geological restraints as the ground the BTES is placed in must have high thermal conductivity to reduce the thermal losses from the system and low amounts of ground water (Guelpa and Verda, 2019). Tank and Pit thermal storage encase a medium that is most commonly water. However, other mediums such as concrete, paraffin or magnetite brick however the practicality for these systems for individual houses found that at maximum weekly storages could only be practical for small well insulated dwellings thus season was judge to be far impractical however this analysis has net been applied to DHN when storage could become more viable due to economy of scale (Allison *et al.*, 2018).

2.4 Heat Emitters

The reduction in in the supply temperature of the DHN will also see a dramatic reduction of heat output from the heat emitters that are currently in place at the campus. Thus, the thermal performance of the building will need to be improved to allow for the ultra-low temperatures. It will be investigated in the thesis if these upgrades will be enough to create a thermally comfortable environment or if the emitters will ultimately need to be replaced by larger or more efficient variants. Reduction of DHN supply and return temperatures has been achieved without replacing the current heat emitters as shown in (Østergaard and Svendsen, 2016) however for this particular example is for 4^{th} generation DHN not 5^{th} generation. There is also the additional problem when considering that the case study is based in Denmark and not the UK where the heating market lags behind the rest of mainland Europe and the emitters most commonly used are designed for high temperature with low temperature differences between supply and return (Tunzi *et al.*, 2018). Therefore, it is not anticipated that the current emitters will be able to cope with the drop-in temperature thus replacements must be considered such as bigger/ more efficient radiators, ceiling heating panels and wall heating panels. Underfloor heating has a natural synergy with ULTH as the maximum temperature that can be used is 30^{o}C however, there are massive costs and time associated with retrofitting UFH, therefore it is not being considered for this thesis.

2.4.1 ULT Radiators

Radiators have advanced rapidly in recent history to accommodate for lower temperature in aid to reduce carbon emission. Advancements such as convection fins and placing these fins in contact with hotter channels and reducing water content and then flattening the fins. This has allowed for temperature as low as 45^{o}C to be utilised in regular radiators and led to an 87% improvement in material efficiency (Iivonen, Harrysson and Kurnitski, 2012). Radiators of this efficiency are commonly used in countries such as Denmark and Europe however the UK is far behind where radiators are commonly use high supply temperature and small ΔT (Tunzi *et al.*, 2018). There are also options such as forced convection radiators that can either utilise ventilation placed behind the emitter or fans below, but ventilation radiators like UFH are particularly difficult to retrofit because they require a hole in the wall behind the radiator there are also doubts that this improvement alone would increase thermal comfort. Forced convection radiators can also come with a fan below the radiator but this variant causes at lot of noise that would not be suitable in a university campus setting. The output of radiators can be calculated by the equations 2, 3 and 4;

$$P = k.A.\Delta\theta_{lmtd}^{n} \quad (2)$$

$$\Delta\theta_{lmtd} = \frac{\theta_{water,in} - \theta_{water,out}}{\ln\left(\frac{\theta_{water,in} - \theta_{air}}{\theta_{water,out} - \theta_{air}}\right)} \quad (3)$$

$$\frac{1}{k} = \frac{1}{\alpha_{ins}} + \frac{\delta}{\lambda} + \frac{1}{\alpha_{out}} \quad (4)$$

Where, A=surface area of the radiator (m^2), k=total heat transfer coefficient (W/m^2K), n=radiator exponent, usually set to 1.3, α_{ins}=heat transfer coefficient between internal water and radiator (W/m^2K), α_{out}=heat transfer coefficient between radiator and air that contains radiative and convective parts (W/m^2K), λ=conductivity (W/mK), δ=radiator wall thickness (m), $\Delta\theta_{lmtd}$=logarithmic mean temperature difference between heated surface and ambient air (°C), θ_{air}=mean room air temperature (°C), $\theta_{water, in}$=water inlet temperature (°C), $\theta_{water, out}$=out water outlet temperature (°C) (Ovchinnikov, Borodiņecs and Strelets, 2017).

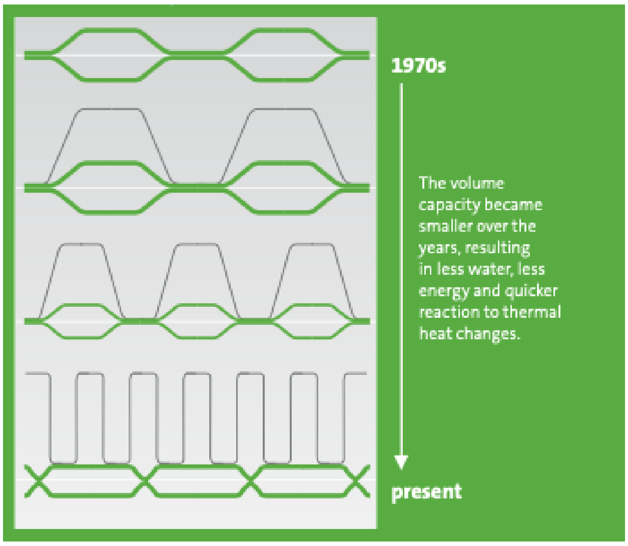

Figure 2-5: Improvement from 1970 (Iivonen, Harrysson and Kurnitski, 2012).

2.4.2 Radiant Heating Panels

Radiant wall panels run the pipes through the wall and using a combination of thermal insulation and air voids, ensure that the heat is directed to the required room and negates the influence of humidity construction of a wall panel can be seen on Figure 2-6. Radiant panels are better suited to low supply temperatures as they have the ability to use the full area of a wall this also leads to better thermal comfort as the heat is dissipated at the full height of the wall which is felt more evenly from head to toe for users of the room. They also have the added synergy to 5GDHC as they have also been used for cooling. Wall panel heating has been seen to be more energy efficient when compared to radiator heating even without additional insulation (Bojić *et al.*, 2012). Radiant panels can also be hung from the ceiling, these have similar advantages in terms of thermal comfort because again they can utilise the entire area of the ceiling however they tend to be used in strips but this again does lead to a more even distribution of heat compared to radiators particularly in deep rooms. Ceiling heating panels have been show to provide a more consistent temperature in a room but consume more energy when compared to wall panels however this study was done with the heat supply coming from a gas boiler that has low exergy efficiency thus results may differ with different sources such as heat pumps used in 5GDHC (Bojić *et al.*, 2013).

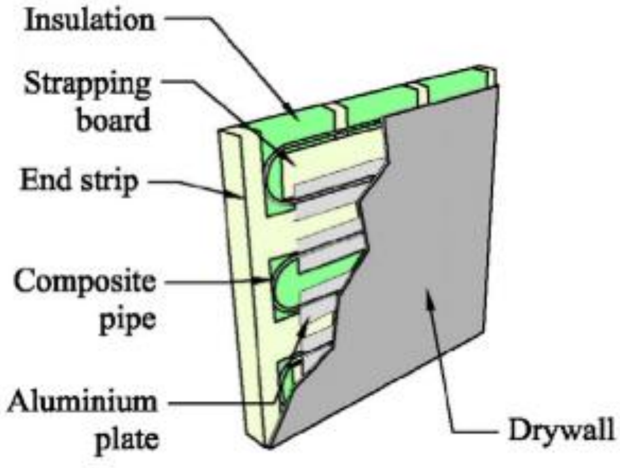

Figure 2-6: Radiant wall panel construction (Ovchinnikov, Borodiņecs and Strelets, 2017).

2.5 Legislation

As mentioned in the introduction the 5GDHCN offer a partial and achievable solution to reductions in carbon emissions in heating and systems like these will play a part in the UK and Scotland government aims of achieving net-zero carbon emissions for 2050 and 2045 respectively (reference). The Scottish Heat strategy estimate that DHN could account for 10% and upwards of Scotland's heat demand and to encourage this there are supportive legislations for DHN themselves through the DHN loan and for the technologies that are used to power the DHN through the Renewable Heating Incentive (RHI).

2.5.1 Renewable Heating Incentive (RHI)

RHI was introduced in late 2011 to give the British public a monetary incentive to switch to renewable heating systems to aid the reduction of carbon emissions. Participants enter a 7-year contact in which they are paid quarterly based on the amount of energy the system produces. The payment for RHI are based on the amount of energy produced by the systems, the money that a participant would receive is based on the technology that they have and the size of the system. See Figure 2-7 for the technologies and sizes with the price in p/kWh. For a participant to receive RHI payments they must have a Microgeneration Certificate Scheme (MCS) for the installation of the system and Energy Performance Certificate (EPC) for the property. Audits can also take place at any time once the system has been installed the participant (Ofgem, 2017). There are also individual requirements for each technology for example biomass systems must comply with air quality requirements and heat pumps must have a greater SCOP above 2.5. It should be noted that WSHP receive the same price as GSHP. As can be seen in Figure 2-5 there have been 20 price changes since the schemes inception in 2011 and there is some hesitation for industry to trust the scheme as there is the possibility of the prices falling off dramatically as can be seen for the biomass systems below 200kW. RHI scheme was scheduled to close to new applicants in March 2021 however has been extended by another year to provide support to projects that were delayed due to COVID-19. RHI was created with ambition that there would be over half a million uptake in systems included in the schemes however the actual uptake has been much less, below 80,000 in 2018 (Swain, 2018). With the current installation rate it would take the UK 1500 years to decarbonise heat therefore it can be concluded that the RHI failed as a policy (Page, 2020).

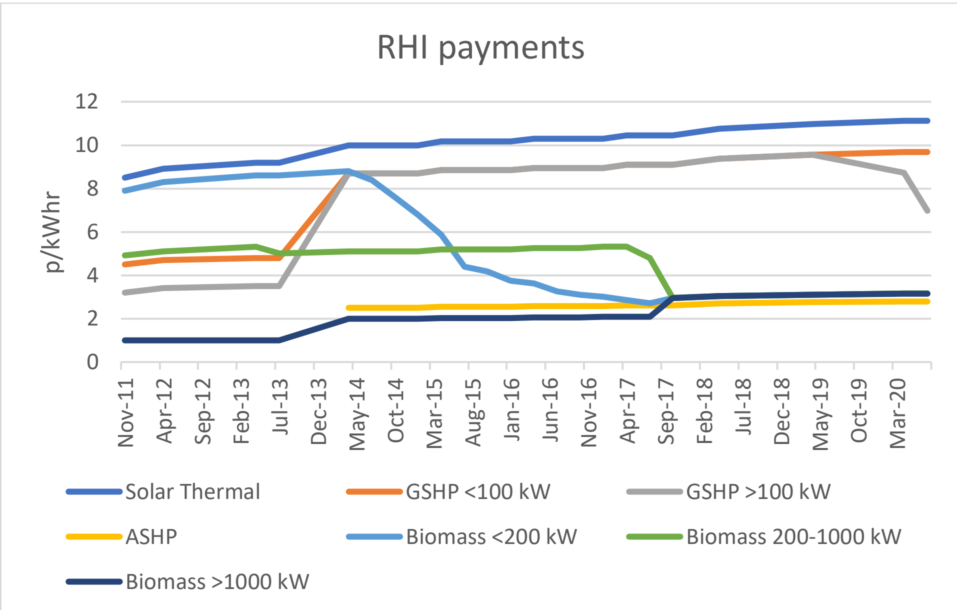

Figure 2-7: RHI payments over time.

2.5.2 Heat Networks Bill

Currently the Scottish government is trying to strengthen policy to support the growth of district heating in Scotland, currently DHN are only accountable for 1% for the heat demand in Scotland but has the potential to be increased to 10% and beyond. The Bill focuses on heat network; licenses, consents, zones and zone permits as well as building assessment reports, powers of license holders and key heat network assets (Scottish

Government, 2020a). The main support that district heating gets at this current time is also summarised in bill; district heating loan fund (DHLF) which is a low rate loan to provide the relief for the upfront capital cost the amount that can be loaned and the length of repayment is largely dealt with on a case by case basis (Energy Saving Trust, 2018). Low Carbon Infrastructure Transition Programme (LCITP) that supports low-carbon projects by assisting to develop the projects business case for funding (Scottish Government, 2015). Another incentive is the continuation of the 50% reduction in non-domestic rates for DHN however this argue as not enough from the industry (Scottish Government, 2017)(All-Energy, 2020).

2.5.3 Legislation Gaps

As has been seen throughout the literature review the UK is behind countries in mainland Europe such as Denmark and Germany in terms of both decarbonisation of heat and DHN. Although the Heat Network Bill does show promising signs that this gap can be narrowed the bill will need to be supported by more legislation that is focused on the decarbonisation of heat. Both of these shortcomings is resolved in most Danish DHN by offering end users of the system a 'motive tariff' that promotes lower return temperatures thus increases efficiency however there is no such precedent for policies similar to this in the UK (Tunzi *et al.*, 2018). There are no policies in place in Europe at the moment that promote the use of thermal energy storage nor are there any that economically support the use of waste heat both of which play a vital part of a 5GDHN.

2.6 Legionella and Domestic Hot Water

As has been stated in the previous sections of the literature review one of the focal points around 5GDHC is the reduction of supply temperature from the DHN. The current system that serves the campus at the University of Strathclyde serves both the space heating and domestic hot water (DHW) therefore it has been assumed that any retrofit should serve the same appliances the one already in place does this then rises the problem of Legionella. Legionellosis is a disease that stems from legionella bacteria, the bacteria forms and multiples in water that is above 20_oC and starts to die off in hours at temperatures at 50_oC and is killed instantaneously at 70_oC and above (CIBSE, 2013a). The bacteria infect humans who inhale the droplets of water that are stored at these temperatures. The disease can be fatal, the last outbreak in Scotland was in Edinburgh in 2012 that saw 53 confirmed cases and 4 deaths (Othieno *et al.*, 2014). The systems temperatures and the legionella growth category they are is can be seen on Figure 2-8.

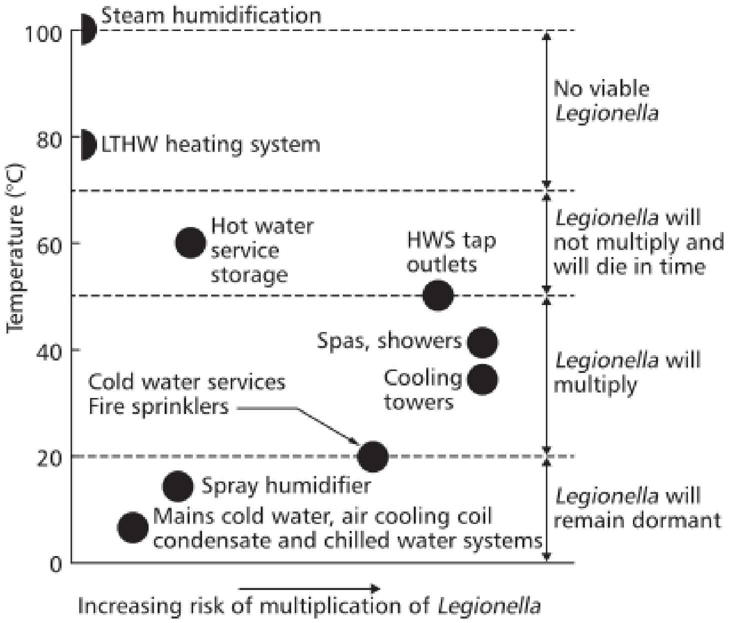

Figure 2-8: System and legionella risk (CIBSE, 2013a).

Solutions to this evolve substations or thermal transforms at each building that is connected to the DHN. For the case study for this project there are already thermal transforms in place at each building however the main use of these systems is to actually bring the temperature down from the supply temperature of around 100-90$_{o}$C to a usable temperature of 45$_{o}$C. The most common method to solve this issue is the utilisation of an emersion heater paired with a hot water tank. Solutions involve having substations within each building connected to the DHN, for 5GDHCN this can involve a heat pump that would use the supply temperature from the DHN to heat water to the values of 55$_{o}$C. These systems paired with an in-line supply tube to reduce return flow temperature, can reduce the heat loss and the cost of running per year however require a large capital investment (Yang, Li and Svendsen, 2016a). Alternatively instantaneous electric heater can be installed in the DHW pipe after the DHW and even further if the supply of DHW is split for kitchen use the electric heater only need to be implanted in this as these are the only applications that require 55$_{o}$C this solution is the most economic as it does not require storage and reduced the electrical energy use in comparison to the other solutions (Yang, Li and Svendsen, 2016b) .

2.7 Chapter Summary

This Chapter has identified the key areas that would be necessary to consider when trying to implement a 5GDHC system in Scotland. It has illustrated the vast amounts of improvements and changes that would be required to the current system.

An overview of the operation of a DHN and the development of the technology has been described from its inception to the 5GDHC and particularly the temperature focusing on what distinction between the 4th and 5th generation then focusing on the deployment of DHN in Scotland.

Heat pumps are then discussed as there are used to upgrade the heat from the list of potential sources to temperature that can be used for the supply of the DHN, the mechanics and the sources for the heat pump that will undergo feasibility studies and their respective advantages and disadvantages are discussed.

The different options for energy storage and the length of time that the energy can be stored for these options will then be taken forward for the feasibility in chapter 4.

Heat emitters are then discussed as these will be evaluated to evaluate if typical emitters in the UK will be able to adequately heat the room if not replacements and retrofit options are also discussed.

The legislation support that is available for technologies and systems that are focused on the decarbonisation of heat are analysed as well possible future legislation that could further improve the feasibility of 5GDHC.

As the 5GDHC operates at temperature that legionella bacteria can multiply at, possible mechanical options that can be used to address this are explained.

3 Current DHN at the University of Strathclyde

3.1 Summary

The University of Strathclyde is located in the city centre of Glasgow, the university has over 20,000 students that serves both research and teaching. The first stages of the DHN was completed in 2018 however the network was built in 3 phases and also built with further expansions in mind. The majority of the buildings connected to the DHN are teaching/ research buildings with the exception of the student union and the sports centre.The buildings that are connected to the DHN range from the royal college building that was first opened in the 1910's which is a typical Victorian building which was originally heated with steam. Also connected to the DHN is the Technology Innovation Centre (TIC) that was opened in 2015 with modern energy efficient systems. Inadvertently the two previous mentioned buildings are also the highest consuming buildings as can be seen in section 3.3.

3.2 System Specification

System specifications of the current DHN at the University of Strathclyde have been gathered from documents provided by the Operation and Maintenance department of the university and from the Vital Energi website(Vital Energi, 2016) The DHN layout and the system architectural drawings can be seen in Appendix A.

Main Energy Production	3.3MWe CHP
Back up energy Production	8MWth gas boilers x3
Pipe layout	Twin pipe
Distribution Median	Water
Temperature (supply/return)	95-65$_{o}$C (73 used in buildings)
Thermal Storage	100m$_{3}$ Tank
Length of Pipe	2.2km underground 4km above
Typology	Branch
Heat Type	Space Heating and DHW

Table 3-1: Current DHN specifications

3.3 System Demand

The system demand was gathered through monthly reports that are provided to the O&M from Vital Energi. The demand per building has been total demand on the system has been presented on Figure 3-1 and 3-2 respectively.

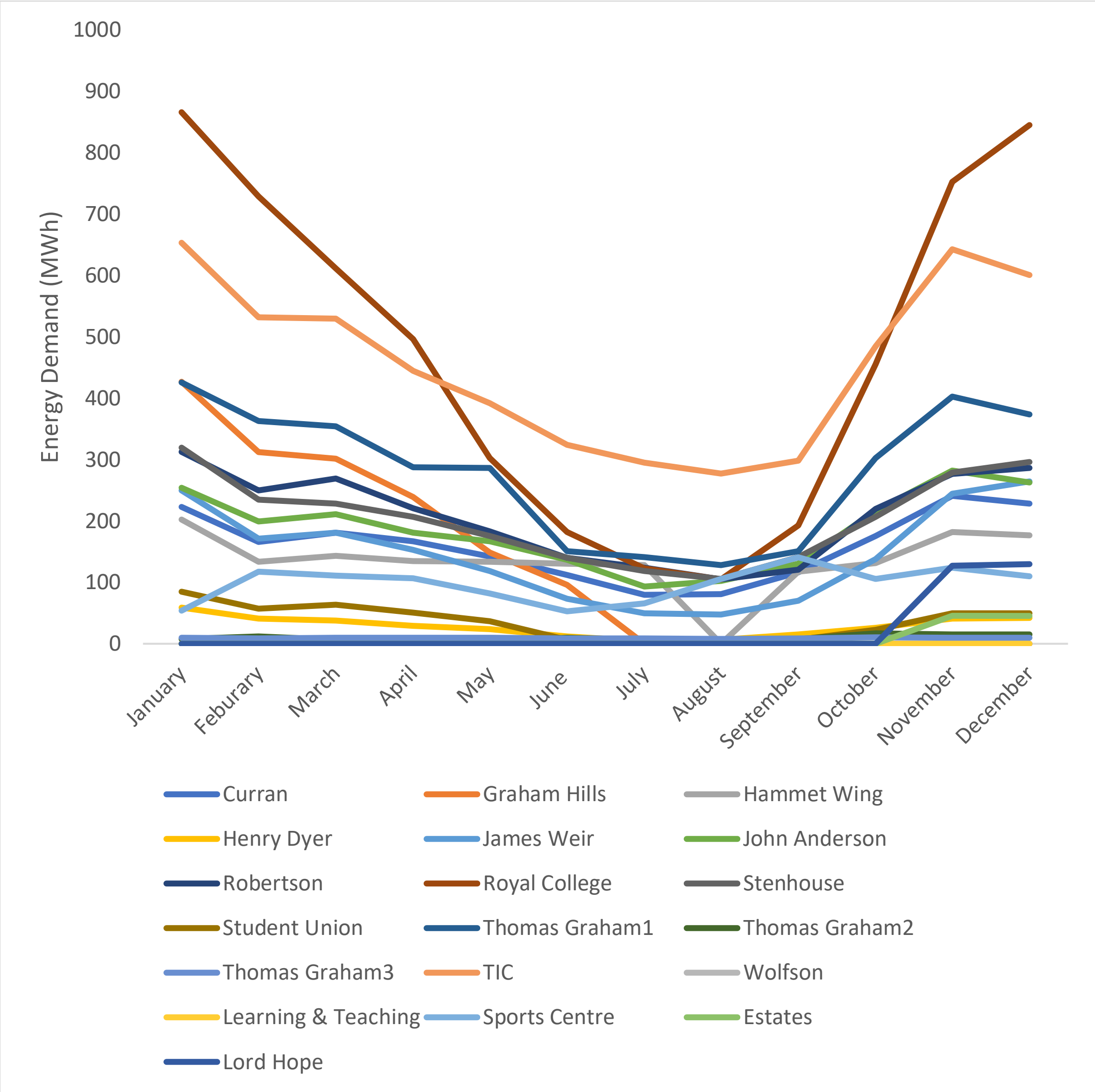

Figure 3-1: Energy demand on DHN per building connected.

Figure 3-1 shows the energy demand for every building connected to the DHN however, it should be noted that that the Wolfson and learning & teaching buildings are currently in reconstruction therefore show a demand of 0 throughout the year however it is anticipated once reconstruction is finished they will be reconnected to the building.

Similarly, Estates and the Lord Hope building were only connected to the system on the November of this year so show a demand of 0 until then.

It can be seen that the Royal college has the highest demand of the buildings connected to the DHN this is most likely because of the building being over 100 years old. It is for this reason that this is the building the model will be based on. Contrarily the second highest demand was the TIC building which is the most modern building connected to the DHN. The EPC of both buildings can be seen on Appendix B for comparison however, it should be noted that the EPC for the Royal College was conducted in 2009 and many of the improvements suggested have been implemented such as double glazing and LED lighting.

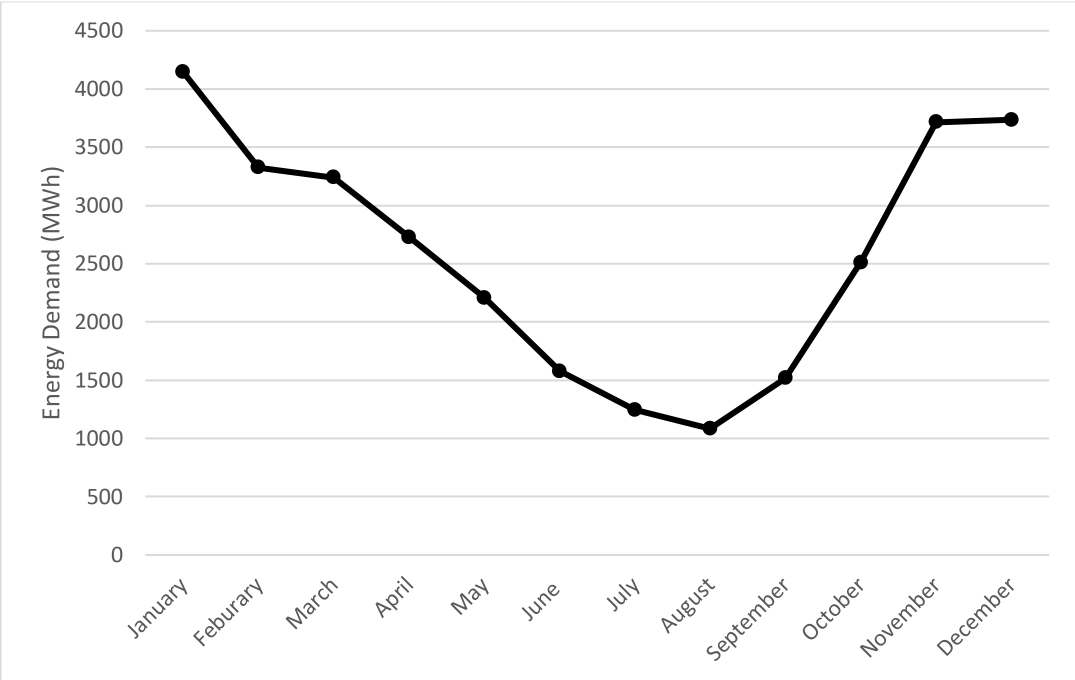

Figure 3-2:Total demand of the current DHN.

Figure 3-2 illustrates the total demand on the DHN. It’s typical of that of a northern hemisphere heating demand with the majority of the demand occurring in the late Autumn-Winter months November- February, with little demand in comparison in the summer months June – August.

4 Resource Investigation

To evaluate what resources can be used to power the proposed 5GDHC system the current DHN and a further 500m and 1km radius will be considered. Resources out-with this area will not considered due the costs it will take to dig out roads to lay underground pipes and pumping costs that would be required to utilise these resources. Solar thermal collectors will be assessed as well as waste heat from cooling towers in the area and locally in the university campus. Resources for the source of the heat pump; air, ground, water and ground water. Ground and ground water will also be assessed in terms of storage for BTES and ATES respectively. Table 4-1 shows the monthly averages of air and river temperature along with solar irradiance that will be used for assessment.

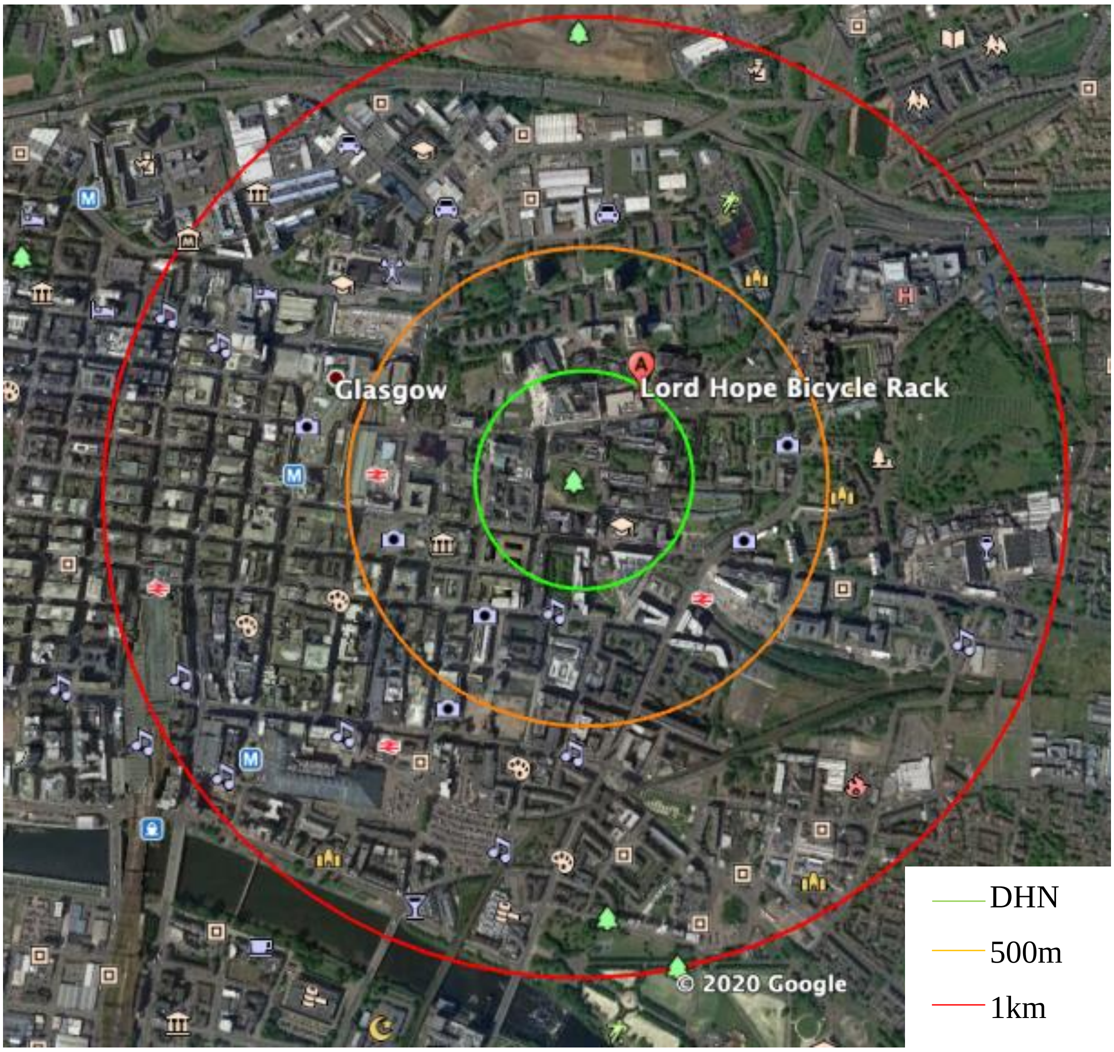

Figure 4-1:Catchment areas that encompass DHN, 500m and 1km radius from DHN

Month	Ambient Air temperature (oC)	River temperature (oC)	Solar Irradiance on a horizontal plane (W/m2)
January	4	7	413
February	4.3	6.6	1030
March	5.7	6.3	2071
April	7.8	7.3	3537
May	10.5	8.8	4568
June	13.1	9.8	4680
July	15	11.8	4505
August	14.5	13.2	3641
September	12.3	13.3	2418
October	9.4	12.3	1286
November	6.4	10.9	591
December	4.2	8.7	283

Table 4-1: Glasgow monthly averages (CIBSE, 2015)

4.1 Solar Thermal Assessment

Solar resource is often over-looked in systems in Scotland due to the poor irradiance when compared to locations further South and when they are considered, often PV panels are preferred over solar collectors, however, collectors are considered for this project due to their ability to feed directly into the 5GDHCN particularly to serve the DHW demand. The SAP method for calculating output for solar thermal collectors will be used for this appraisal, Equations 5, 6, 7, 8, 9 and 10 will be used for the assessment.

$$Q_s = A_{ap} \times \eta_0 \times S \times Z_{panel} \times UF \times f_1 \times f_2 \qquad (5)$$

$$UF = 1 - e^{\left(\frac{-1}{H8}\right)} \qquad (6)$$

$$H8 = \frac{S_{available}}{Annual\ Heat\ Demand} \qquad (7)$$

$$S_{available} = A_{ap} \times \eta_0 \times S \times Z_{panel} \qquad (8)$$

$$f_1 = 0.97 - 0.0367\left(\frac{a^*}{\eta_0}\right) + 0.0006\left(\frac{a^*}{\eta_0}\right) \quad (9)$$

$$a^* = 0.892(a_1 + 45a_2) \quad (10)$$

Where Q_s is the output of the solar thermal collector(kWh), A_{ap} is the aperture area of the panels (m2), η_0 is the zero loss collector efficiency, S is the solar radiation on the collector (kWh/m2), Z_{panel} is the over-shading factor, UF is the utilisation factor, f_1 is the collector performance factor, f_2 solar storage volume factor, H8 is the ratio of annual solar energy available to annual heating load, a_1 first order heat loss coefficient and a_2 is the second order heat loss coefficient.

The roofs of the buildings that are connected to the DHN were mapped on Google Earth Pro with exception to the building that are under construction and the TIC building as this building already has photovoltaic panels installed. The total roof area were calculated to be 31098m2 as these roofs are heavily used for HVAC systems, it is assumed that if solar thermal collectors were to be used, they would only utilise 10% of this area. The solar collector selected for this study was the HP200 manufactured by Kingspan (Kingspan Solar, 2018) where the aperture area was 3.23m2 and area of the panel it total area of the panel is 4.43m2, zero loss collector efficiency is 0.75, the value for S in each month a can be seen on Table 4.1, overshadowing was assumed to be 1 as these panels will be horizontal on roofs, a_1 is 1.55W/m2K and a_2 is stated as 0.006W/m2K. The monthly outputs can be seen below Figure 4-2.

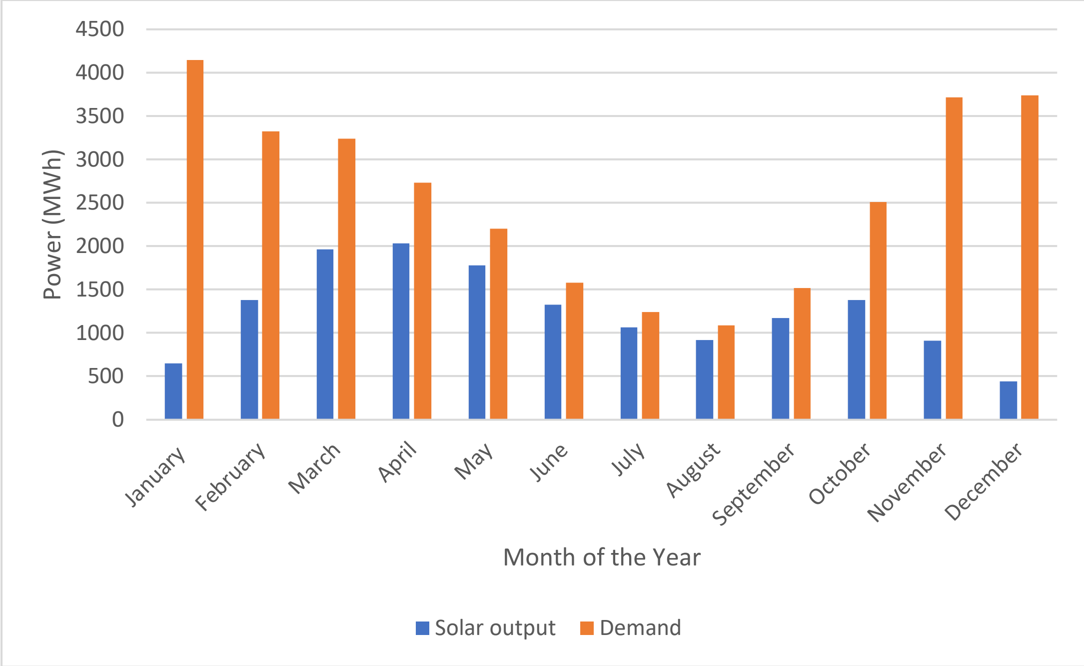

Figure 4-2: Solar Output in Comparison to Demand of DHN

4.2 <u>Waste Heat</u>

Possible waste heat sources within the defined catchment area have been identified through the Scottish Heat Map using the cooling tower layer, this is presented in Figure 4-3. There are also two local sources already with the DHN that have also been considered.

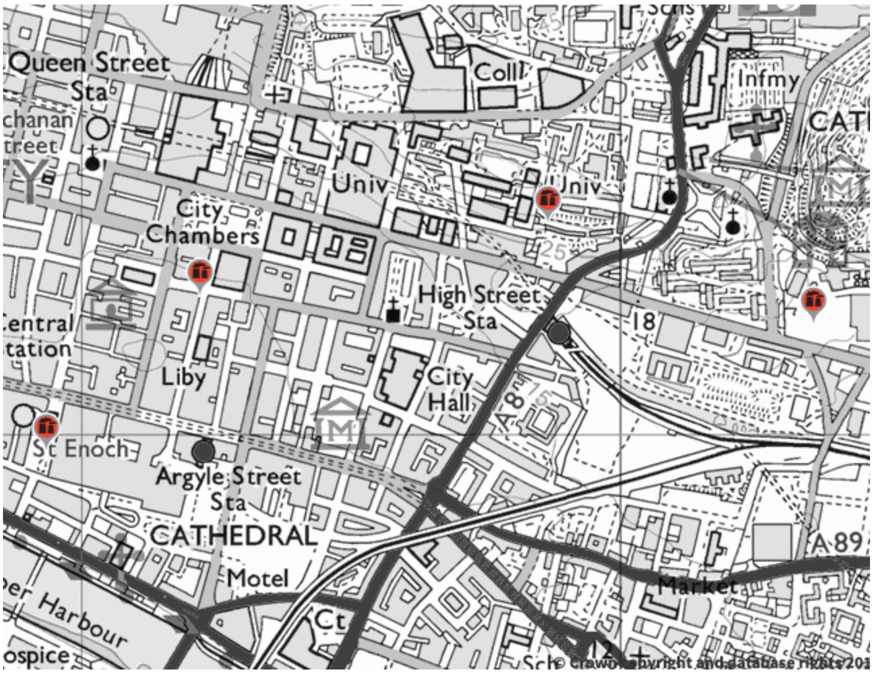

Figure 4-3: Cooling towers in the DHN catchment area (Scottish Government, 2020b).

The only heat source that could be identified is the Wellpark brewery that can be seen on the very right of Figure 4-3 therefore the other 3 are not assessed. As well as the Wellpark brewery there is also two data centres that are located within the university campus.

4.2.1 Brewery

The Wellpark brewery is located within the 500m radius of the Strathclyde DHN illustrated on Figure 4-1. The brewery has the potential to contribute to DHN due to their high flue gas temperatures that are given off during the chemical process. The amount of heat that can be extracted is however limited as reducing the temperature to below 150$_o$C effects the buoyancy of the flue streams thus leading to additional induction fans being installed (Church, 2015). A study on a medium sized brewery in Scotland found that heat recovery measures in the brewery were able to reduce hot utility demand by 1030MWh per year (Eiholzer *et al.*, 2017). The brewery in the study produces 25,000,000L of beer per year and operates 300 days of the year and thus would be able to provide heat for the majority of the year. Unfortunately, the production rate and operating days of the Wellpark brewery couldn't be obtained however it is assumed that due to its stature that the Wellpark brewery could provide more heat than the brewery studied therefore could have a substantial role in a 5GDHCN at the University.

4.2.2 Data centres

With the increase use of online resources data centres have become more abundant in in all areas. The University Campus also has its own data centre and back up that is located in the Curran and Graham Hill respectively. Data centres have been assessed to have a typical value of 1-4MW of heat available (Revesz *et al.*, 2020). However, it is unknown what the sizes of the data centres at the university are, therefore cannot be gauged on how much they can contribute but due to these being within the network it would be nonsensical not to utilise them.

4.3 Source for Heat Pump

4.3.1 Air

The temperature of the air is not restricting aspect for the possibility of powering the 5GDHCN however, currently the largest ASHP that is used to provide heat to a DHN has the capacity of 400 kw that is used to power a DHN in Glasgow (Star Refrigeration, 2020). This would not be sufficient to meet the demand of Strathclyde DHN. If the DHN were to be changed from one centralised energy centre to several decentralised centre it could open up the possibility for ASHP to be used however this is without the scope of this thesis. Thus, the resource will not be considered further.

4.3.2 Ground/ BTES

As previously stated GSHP have come in two main types of horizontal and vertical with the horizontal being at a depth of 0.8 to 2m and vertical raging from 100 to 200m. Due to the lack of space in the area of the DHN only vertical will be considered for this project. Although the vertical variant takes up less space each U bend borehole pipe usually has a diameter around 0.15m and each bore hole must be spaced at least 5m away from each other (CIBSE, 2013a). The possible spaces that can be used for the boreholes can be seen on Figure 4-3, all of them are in close proximity to the university however even these spaces may not be suitable as all of them are currently used for circulation between buildings in the campus and its unknown if these open spaces would be sacrificed for a proposed 5GDHC.

Figure 4-4: Open spaces available for potential boreholes for GSHP or BTES.

The areas highlighted in green, Glasgow College (top left), Rottenrow Gardens (centre) and Stenhouse (right), have been measured using Google Earth Pro and the number of boreholes that could be placed with minimum 6m spacing has been calculated using values of depth of 100m and 35W/m the power output for each(CIBSE, 2013b).. The results can be seen on Table 4-2.

Space	Dimensions (LxW m)	No of Borehole	Capacity (kw)
Glasgow College	76x90	252	882
Rottenrow Gardens	35x67	66	231
Stenhouse	35 x60	60	210

Table 4-2: Breakdown of available area and capacity.

The total of the three areas comes to a capacity of 1.3MW. Although this may not be big enough for the main production of back up this would provide a substantial energy storage thus it would be suggested that boreholes are to be used to be used for TES rather than direct source to a heat pump. Although 100m depth is shallow in comparison to other GSHP systems it however a full borehole analysis would need to be conducted before this technology was implemented. As well as this the topology of Rottenrow Gardens may be an issue as it is on a very steep hill.

4.3.3 Ground Water/ATES

There are several 5GDHCN that are powered by ground water and this is also used for ATES as described in section 2.3.2. However, there are also 5GDHC network that utilises disused mines that have be filled with water to supply the heat pump in the Netherlands. There is a possibility that a similar design can be used in Glasgow as there is many of these disused mines that can be seen on Figure 4-4. It can be seen that there is one minework that is within the 1km catchment area at Bellgrove.

Figure 4-5: Mine Shafts in Glasgow (Coal Authority, 2018)

The British Geological Survey has started to conduct surveys on the abandoned mine works to evaluate the geothermal energy that they could provide. The survey will concentrate on the mines located in Dalmarnock which is in the very bottom right corner of Figure 4-3. The preliminary report on this study estimated that the mine water temperature could be as high as 12$_o$C which would make it an excellent resource to feed into the heat pump for a 5GDHCN (Monaghan,Starcher, Barron, 2020)However this study is out with the catchment area and the study is only within the preliminary stages thus accurate details of the mines are yet to be confirmed. For example if there is enough resources there for the mine water to be used for a considerable period of times as this was an issue in the DHN in the Netherlands that was resolved through utilising more mines(Verhoeven *et al.*, 2014) Therefore, the mine water/ ground water source for the Heat pump and ATES although promising cannot be considered further due to the lack of detail for the mines in the Glasgow area but should be considered once the BGS publish their full findings.

4.3.4 River

It can be seen on Figure 4-1 that the river Clyde is just within the 1km catchment area, the river has enormous potential to be the source of the heat pump in either a closed or open loop system. The total energy that can be extracted from the river is given in the following equation 11;

$$Q_{in} = \dot{m}\ \rho\ C_p\ \Delta T \qquad (11)$$

Where Q_{in} is the heat that can be extracted from the river (J), $\dot{m}$ is the mass flow rate of the river that can be used, (m^3/s), ρ is the density of water (997 kg/m^3), C_p is the specific heat capacity of water (4200 J/kg^oC) and ΔT is the temperature difference from the water entering the he heat pump and returning to the river.

The closest station to the DHN that measures the mass flow rate of the Clyde is located at Daldowie which is roughly 8km from the DHN. The mass flow rate for the Clyde for the period 1963-2019 exceeds 9.752 m^3/s 95% of the time, it assumed that only 10% of this would be captured therefore 0.9752m^3/s will be used (NRFA, 2020). The temperature of the Clyde can be seen on Table 4-1 and it’s advised that during feasibility studies that 3^oC is used; as the minimum temperature in the Clyde is 6.3^oC this can be used without risk of freezing (CIBSE, 2016a).

$$Q_{in} = 0.9752 \times 997 \times 4200 \times 3 = 12250657.4$$

Therefore, the river Clyde could be the source for a 12.25MW heat pump.

5 Model

To assess the possibility of utilising a ULTH in the building stock at the University of Strathclyde a section of the Royal College (RC)was modelled in the software ESP-r.

"*ESP-r is a long-established building simulation tool that allows the energy and environmental performance of the building and its energy systems to be calculated over a user-defined time interval (e.g. a day, a year, etc.). The tool explicitly calculates the transient energy and mass transfer processes underpinning building performances"* (Allison *et al.*, 2018).

building was chosen due to having the highest heating demand whilst being the oldest building connected to the DHN. The floor plan of the section of the building that was modelled and the model itself can be seen on Figure 5-1 and 5-2 respectively, this model will focus on the two rooms RC426 and RC422. The surrounding circulation and RC424 were modelled to increase the accuracy of the model. The base model was calibrated using the real-life data illustrated in Figure 3-1 using the annual data of the RC by dividing the floor area of the classrooms against the usable floor area of the RC and the percentage calculated and used to adjust the annual demand. To ensure that the correct capacity is used for each model, each model (Calibrated, Retrofit A, Retrofit B and Retrofit C) will first be simulated with an abundant amount of heating capacity, 30kW and 10kW for RC426 and RC422 respectively, and will be judged over a period of a working week January (10_{th}-14_{th}). The 90th percentile of the heating load will be calculated and used as the correct heating capacity for that model. The calculated heating capacity will then be implemented into the model and simulated again to calculate the annual energy delivered to the zones and the thermal comfort during the same week the heating capacity was based on. Thermal comfort will be judged on PMV, a PMV of between -0.5 to 0.5 which corresponds to less that 10% dissatisfied occupants. The thermal comfort the percentage of the occupied hours between these two values will be calculated and the retrofit models will be compared against that achieved by the Calibrated model. Using the calculated capacity for each of the models the area of the heat emitter that would be required for supply temperatures of 55, 45 and 35_{o}C will be calculated using Fourier's law shown in equation 2-4 and explained in section 2.4, for the total heat transfer coefficient (4) the radiator is assumed to give aluminium a conductivity of 225(W/mK) and both heat transfer coefficients have been assumed as 50 (W/m$_2$) and the thickness of radiator wall of 1.5mm is used. The usable area for for RC426 is the ceiling as this what can be used currently seen on the right side of Figure 5-1 and for RC422 the two external walls minus the area of glazing and frame.

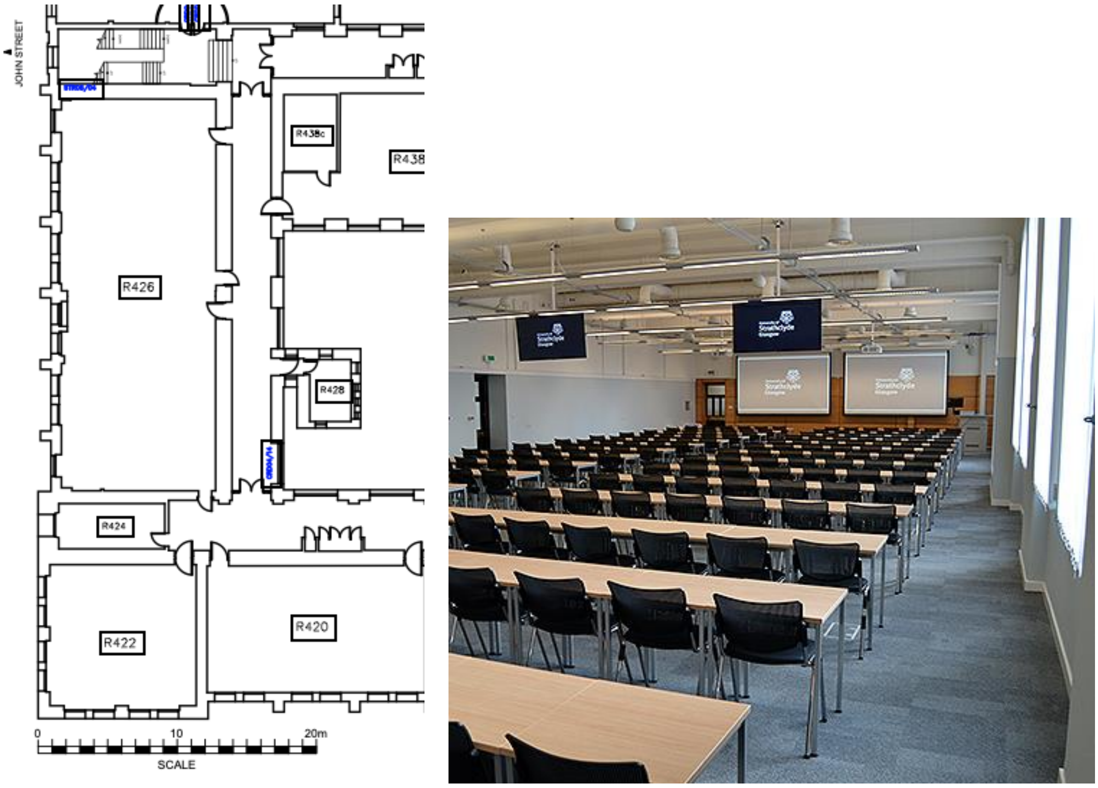

Figure 5-1: On the left is the floor plan of the section modelled and picture of RC426 on the right

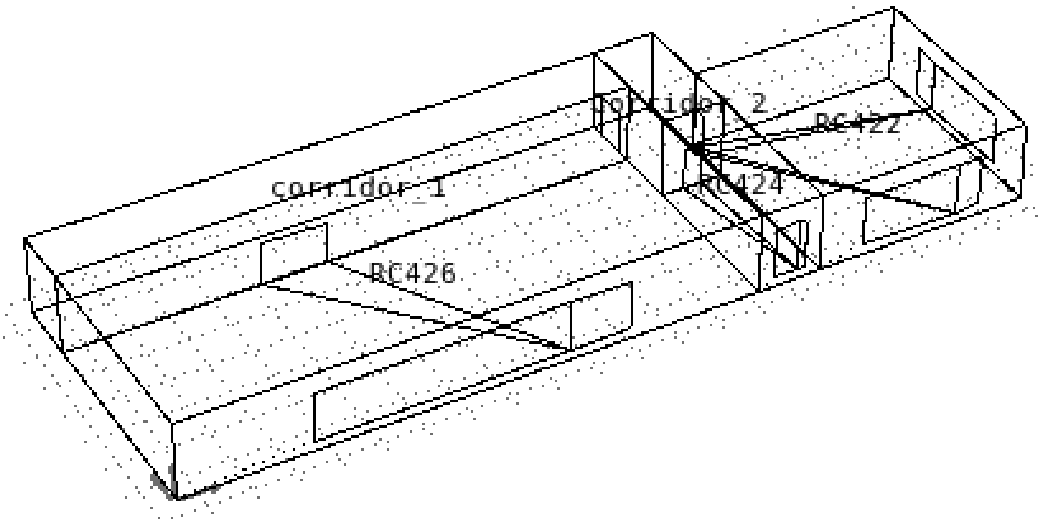

Figure 5-2: Model of section of 4th floor of the Royal college

5.1 Model Characteristics

The construction materials are consistent in each room with the exception of the floors that are carpeted in the rooms and linoleum in the corridors. Assumptions that have been made for the geometry of the building is that the height of the rooms is 4m as well as the height of the windows being 2.5m, the frames of the windows have also been assumed to be 20% of the total area of the window. Simplifications have been applied to the model that have seen the multiple widows that are on each external wall on RC426 and RC422 have been combined into one as well as the frames for each external wall. The ceilings and floors of each zone are connected to similar zones with 0^oC temperature offset as well as all internal walls that are not connected to a zone. An Oban weather file was used for the simulations as this is the closest weather file to Glasgow, the ambient temperature and the solar radiation for this weather file for the month of January can be seen on Figure 5-3 and 5-4 respectively. The heating schedule for all of the cases bar the optimised starts at 7am in an attempt to heat the zone before users entered and stopped at 8pm when the building closes. The set point was set to 22^oC as this was found to be a comfort temperature for Lecture theatres in Scotland (Jowkar *et al.*, 2020) . The casual gains for both RC426 and RC422 has been set as $67W/m^2$ sensible and $50W/m^2$ latent for occupants $12W/m^2$ sensible for lighting and $2W/m^2$ sensible for equipment as is advised for building simulation for lecture theatres (CIBSE, 2015). The filtration of the zones were based on guidance that advised 3/L/S/person the capacity of RC426 is giving as 180 from the university estates department when booking the room and the capacity of RC422 was assumed to be 60 giving the capacity of classrooms of similar sizes, which gives a value of $0.54m^3/s$ and $0.18m^3/s$ for the two rooms respectively (CIBSE, 2016b). For the thermal comfort analysis, the clothing level was assumed to be 0.7, activity level as 90W/m and air velocity 0.1m/s. For all simulations there were 5 start-up days. To estimate whether the heat emitter size is acceptable or not a maximum of 20% of the usable wall area will be used admittedly this is a lot larger than current standards but as most 5GDHCN utilise floor heating wall/ceiling space will need to be used when retrofitting lower supply temperature to buildings that do not use UFH.

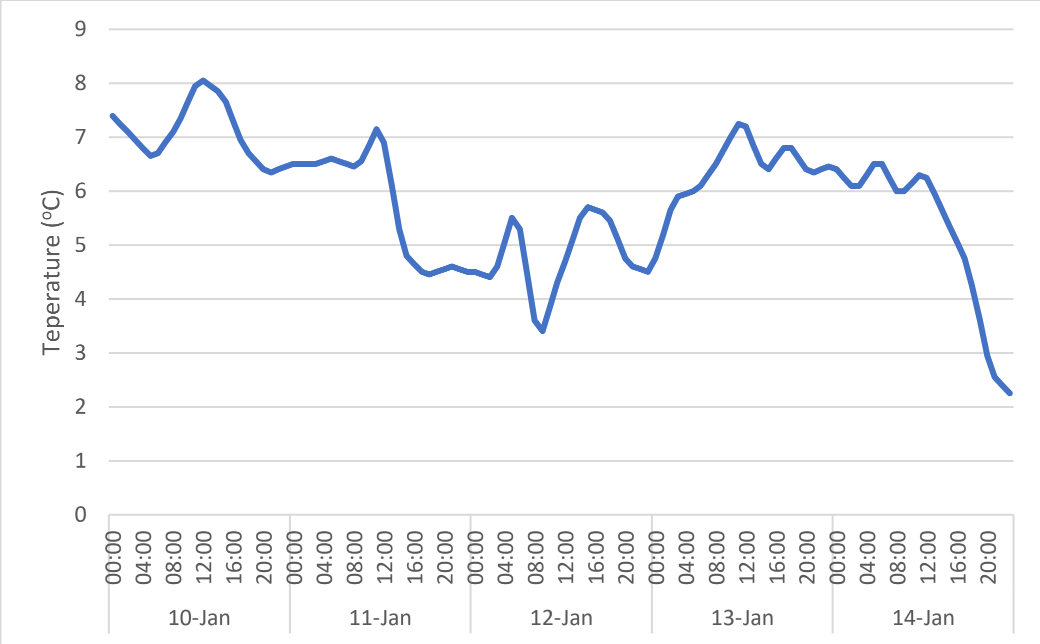

Figure 5-3: Ambient outdoor temperature with week beginning the 10th highlighted

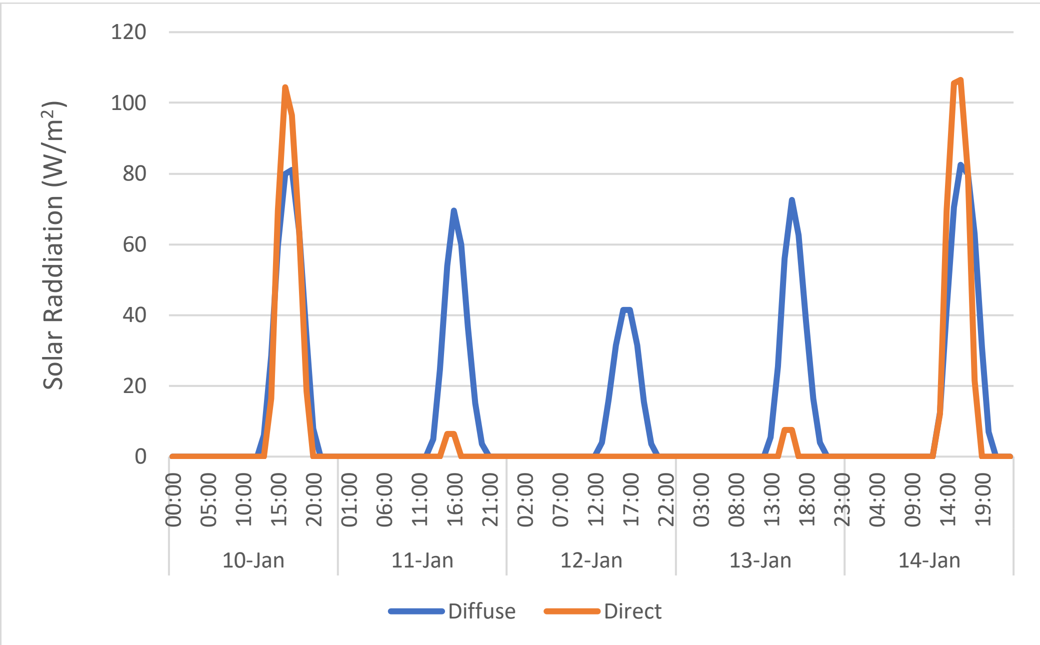

Figure 5-4: Direct and Diffuse solar radiation, week beginning 10th highlighted.

As can be seen for Table 3-2 the annual energy delivered to the RC was 5659.8MWh, the base load of 104.9MWh measured in August was assumed to serve DHW which is not considered in simulation results, this base load was assumed uniform for each month giving an annual energy delivered for space heating of 4401MWh. The gross area of the Royal College was measured to be 36000m2 and the area of the two classrooms is 414m2 thus comprises 1.16% of the gross area of the Royal College, therefore, this should consume 8824kWh. The material was chosen to get as close to this value with still maintaining a realistic material such as the external walls having to be made of sandstone. The list of materials used for the calibrated model and the energy delivered to the model can be seen on Table 5-1 and 5-2. More detail of the results for the simulation of this model can be found in Section 6.1.

Material	U-value (W/m$_2$K)	Construction layers (mm)
External wall	1.561	Sandstone (150)
		Chippings (100)
		Sandstone (100)
		Gap (20)
		Dense Plaster (30)
Internal Wall	2.294	Dense Plaster (30)
		Outer Leaf Brick (140)
		Dense Plaster (30)
Ceiling	4.976	Gypsum Plaster (13)
Floor	1.458	Grey Wilton carpet or linoleum (6)
		Cellular rub underlay (6)
		Plywood (18)
		Gap (100)
		White Gypboard (12.5)
Glazing	2.811	Plate glass (6)
		Gap (12)
		Plate glass (60
Frame	1.696	Softwood (55)
Internal Door	3.316	Oak (25)

Table 5-1: Materials with U-values and construction layers used for calibrated model.

In an attempt to breakdown what retrofits would be more effective in cutting the energy delivered to provide a thermally comfortable space thus cutting down the required energy capacity the retrofits were done in groups, the first Retrofit A tackled the external walls and the ceilings in the model due to the U- value being much larger that

Scottish building standards of 0.27W/m$_2$K, and the ceilings due to the material being the highest U-value of the materials used. B was the internal walls and the floors and C the glazing and frames. The heating scheduled hours were extended in order to counteract the slow response time that comes with lowering the supply temperature to heat emitters. The retrofit materials can be seen for A, B and C can be seen on Table 5-3, 5-4 and 5-5 respectively.

Material	**U-value (W/m$_2$K)**	**Construction Layers**
External Wall	0.541	Sandstone (150)
		Chippings (100)
		Sandstone (100)
		Polyurethane foam (40)
		Gypsum plaster (20)
Ceiling	1.357	Roof insulation (100)
		Gypsum Plaster (13)

Table 5-2: Materials that are used for retrofit A.

Material	**U-value (W/m$_2$K)**	**Construction Layers**
Internal Wall	1.167	White Gypboard (40)
		Dense Plaster (30)
		Outer Leaf Brick (140)
		Dense plaster (30)
		White Gypboard (40)
Floor	0.165	Grey Carpet (6)
		Cellular Rub Underlay (6)
		Plywood (18)
		Kingspan (100)
		White Gypboard (12.5)

Table 5-3: Materials used for Retrofit B.

Material	U-value W/m$_2$K)	Construction Layers
Glazing	0.89	Clear Float (6)
		Gap (12)
		Clear Float (6)
		Gap (12)
		Clear Float (6)
Frame	1.357	Western Larch (25)
		Cork Insulation (24)
		Gap (5)
		Fir (10)

Table 5-4: Materials used for Retrofit C.

6 Results and Discussion

As discussed in section 5 the results will be focused on reducing the heating capacity of the model whilst still maintaining the level of thermal comfort that was first achieved in the model. This reduction in capacity is done to enable lower temperature that are used in 5GDHC.

6.1 Base Model

As can be seen from Table 3-2 the annual energy delivered to the RC was 5659.8MWh, the base load of 104.9MWh measured in August was assumed to serve DHW which is not considered in simulation results, this base load was assumed uniform for each month giving an annual energy delivered for space heating of 4401MWh. The gross area of the Royal College was measured to be 36000m^2 and the area of the two classrooms is 414m^2 thus comprises 1.16% of the gross area. The deviation from the calculated and measured data can be seen on Table 6-1.

Zone	Energy Delivered (kWh)	Energy per m^2	Deviation from measured data (%)
RC426	27508.18	90.61	
RC422	7457.71	67.64	31.44
Total	34965.9	84.5	

Table 6-1:Energy delivered to the model per zone.

Table 6-1 shows the data on the energy that is delivered to the calibrated model. There is no surprise that the energy delivered to RC426 far outweighs that of the energy delivered to RC422 due to the much larger floor area. What is interesting to note that even when the floor area is taken into account the energy delivered to RC422 is more than 25% less than that of RC426 even given that it has more external wall are per floor area, this further emphasises the sheer amount of energy that is required to heat a room of that volume. It can also be seen that the model data has a deviation 31.44%. The ASHRAE tolerances for calibration deviation is 30% however this is based on hourly data which is not provided for given the context of the study and the multipurpose of the building, therefore, 31.44% is an actable deviation from measured data for the purpose of this thesis (Şahin *et al.*, 2015). What is also surprising of the energy delivered to the model is that it is well under the university campus energy benchmarks set out by CIBSE as 240kWh/m^2, again this benchmark is for total thermal fossil energy and will include DHW which is not simulated however with this taken into consideration the model would still be well under the benchmark (CIBSE, 2008). This benchmark however has come under scrutiny and calls have been made for it to be revised as a study based on university campus in Dublin concluded that the benchmark should be revised to 130 kWh/m^2 and suggested that the benchmark should be broken down to monthly values (Vaisi, Pilla and McCormack, 2018). Even with the dramatic decrease in benchmark the model is still under barring DHW production which is surprising giving the thermal conductivity of the materials used to construct the model.

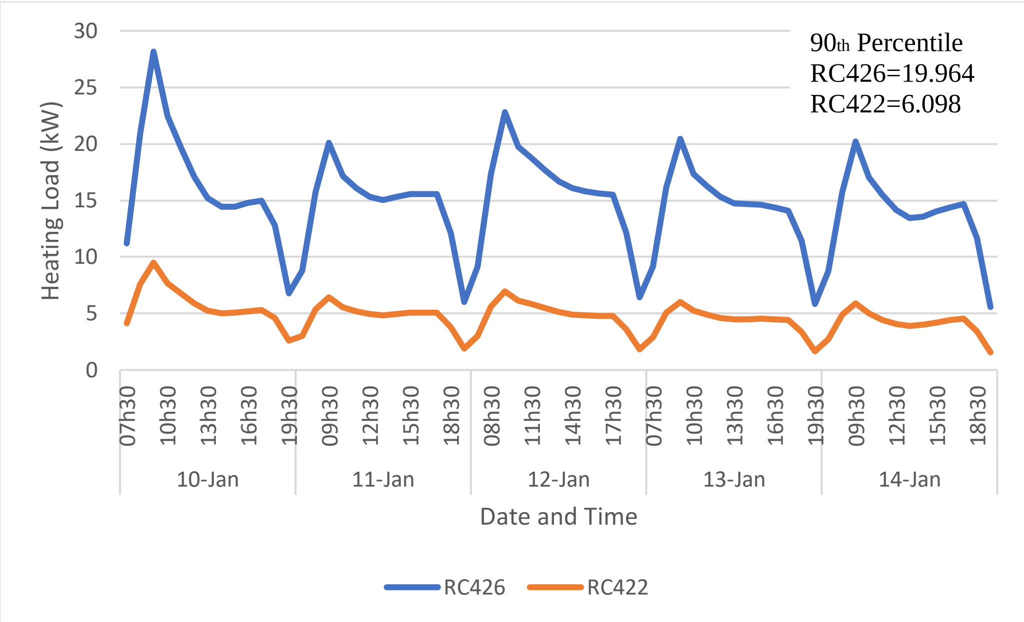

Figure 6-1: Calibrated model heating load

It can be seen in Figure 6-1 that the peak heating load for both zones occurs on Monday morning this is despite this being the warmest day of the week, however this will be due to there being no heating in the building at the weekend therefore temperature will be lower on the morning of the 10th than other weekdays. The daily peak for each zone occurs at 9:30 at which point the load drops and stabilises at around 15kWfor the RC426 and 5kW for RC422. Both zones also see a dramatic drop in load after 18:30 daily below 6kW and 2kW for the respective zones. The 90th percentile was calculated as 19.964 and 6.09 KW for RC426 and RC22 these values were rounded up to the nearest 100W and implemented into the model to produce the following results in energy delivered and thermal comfort.

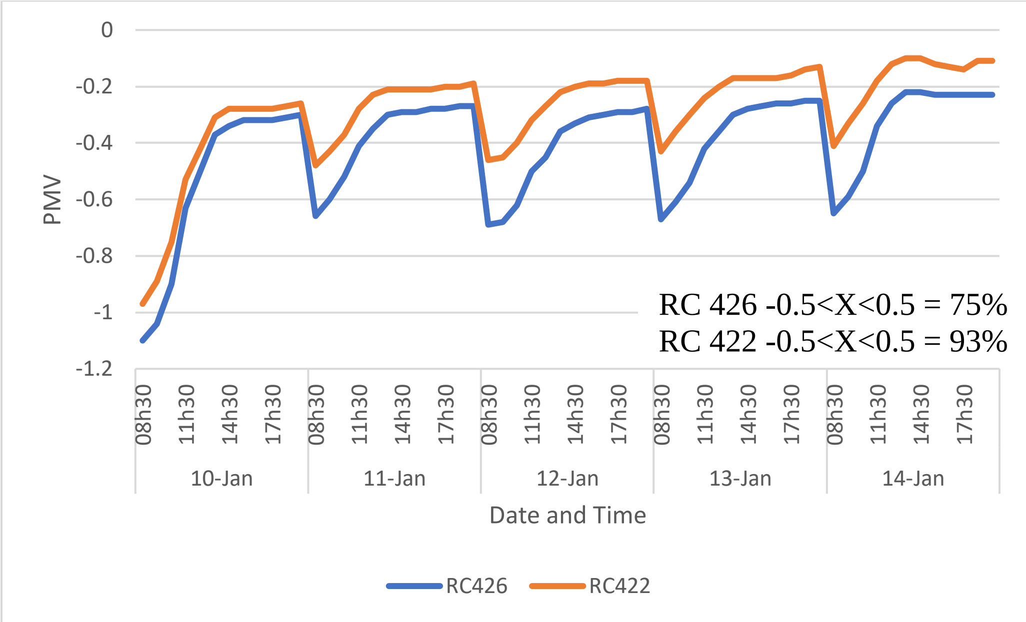

Figure 6-2: Thermal comfort for occupied hours for week beginning the 10th.

Figure 6-2 illustrates the thermal comfort of both the RC 426 and RC 422 the aim was to achieve thermal comfort of between -0.5 and 0.5 PMV. It can be seen that the PMV is the lowest during the Monday morning despite this being the warmest day of the week reaching temperature of $8^{o}C$, this is due to there being no heating in the rooms during the weekends however both rooms reach a PMV of -0.5 by 12:30. Throughout the duration of the working week the PMV is always a negative value maximum being -0.23 and -0.11 for RC 426 and RC 422 respectively meaning that the thermal discomfort felt would be that the room is too cold. It can also be seen that the PMV for RC 422 is on average higher than RC 426 this is due to RC 422 heating capacity being bigger in comparison to that zone with respect to floor area.

RC 426		
Temperature (Inlet, Return)	Area (m^2)	Percentage of Usable wall area
73-63	5.38	4%
55-25	29.97	22%
45-25	41.066	30%
35-25	65.958	48%

Table 6-2: Area of heat emitter require for Calibrated model in room RC 426.

RC 422		
Temperature (Inlet, Return)	Area (m_2)	Percentage of Usable wall area
73-63	1.883	3%
55-25	9.141	17%
45-25	12.525	23%
35-25	20.117	37%

Table 6-3:Area of heat emitter require for Calibrated model in room RC 422.

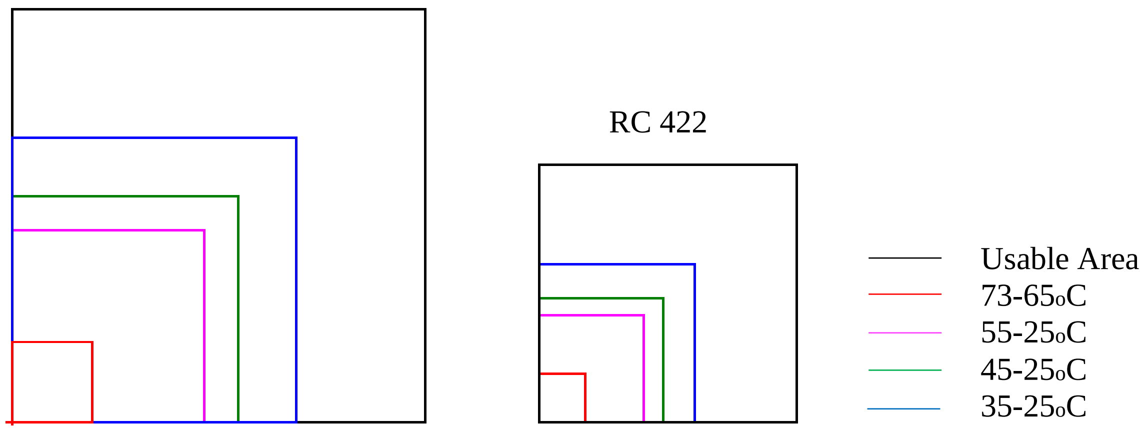

Figure 6-3: Size of Emitters for each supply temperature compared to usable wall area for Calibrated model.

Tables 6-2 and 6-3 show the areas of the heating emitter that would be required for each zone for the calibrated model for the different low supply temperatures, the size of the emitters for the supply temperature that is currently in use in the DHN have also be calculated for the Calibrated model for reference. These calculated measurements have also been illustrated on Figure 6-3 where the areas of emitter and usable area are shown as squares to aid visualisation. It comes as no surprise that the emitters of the low supply temperature are far bigger than that of the supply temperatures already in use. The lower supply temperatures in particular the 35$_{o}$C have values far from feasible with taking up 48% and 37% for RC426 and RC422. 55 and 45 $_{o}$C supply temperature are still impractical but edge closer to a realistic value especially in the case for RC426 where they will be hung from the ceiling.

6.2 Retrofit A

Retrofit A model added insulation to the external wall where there was a gap and also added insulation to all of the internal ceilings, full details of the construction of the two materials can be seen on Table 5-2.

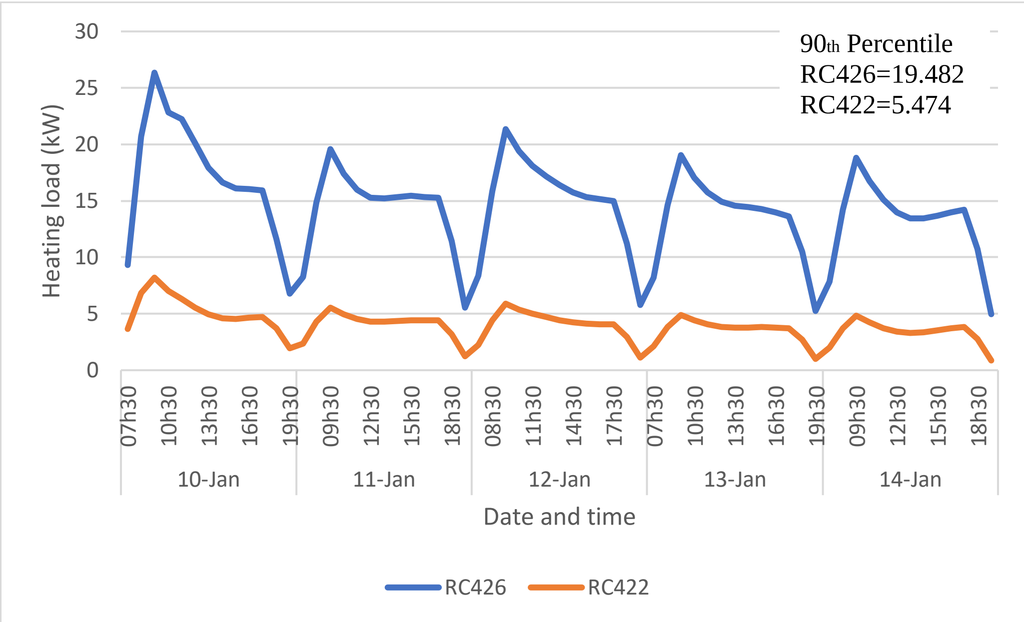

Figure 6-4:Heating Capacity for Retrofit A model.

Illustrated on Figure 6-4 is the heating load for model B. It can be seen that it follows the same pattern as Figure 6-1 with the weekly maximum in Monday morning and daily maximum at 9:30 for the calibrated model however the maximum load for both zones have been reduced, significantly for RC246 which has a maximum load of 26.35kW. For Retrofit A model RC422 has a very uniform load from times 11:30 to 18:30 staying between 5 and 3.2kw with exception of the 10th. A slight decrease across the board for both zones which is expected due to the improved thermal properties, this has led to a reduction 90th percentile value of 19.5 and 5.5 kW for RC426 and RC422 respectively which is a 0.5kW decrease for each zone respectively.

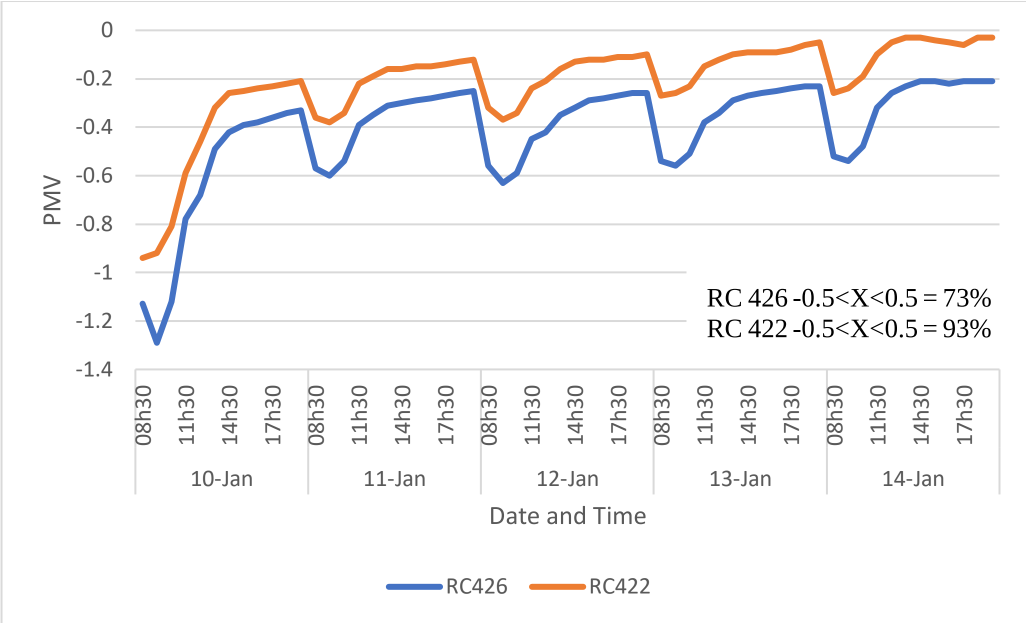

Figure 6-5: Thermal Comfort for Retrofit A.

Figure 6-5 show the results of thermal comfort with the different heating capacities of 19.5 and 5.5kW for RC426 and 422. It can be seen that the reduction of capacity for retrofit has had differing effects from each zone with the percentage decreasing for RC426 and increasing for RC422. Which is particularly interesting due to the decrease in capacity being 2.5% in RC426 when compared to the 8.3% of RC422. A point of interest in this Figure is that the minimum value of PMV occurs at 9:30 after the heating has been entering the room for 2 hours. It can also be seen that RC422 is near reaching 0 PMV on the 14th the closest being -0.03 recorded at both 18:30 and 19:30.

Zone	Energy Delivered (kWh)	Energy per m2	Energy saved compared to Calibrated model (%)
RC426	26875.71	88.52	2.30
RC422	5864.3	53.19	21.37
Total	32740	79.1	6.37

Table 6-4: Energy delivered to Retrofit A and the savings made from last model.

Table 6-4 shows the energy that has been saved from the calibrated model with the given capacities stated above. It can be seen that the majority of the saving is in the

RC422 due to the room having two external walls thus benefiting more from the improved insulation more than RC 426. The overall savings are 6.37%

RC 426		
Temperature (Inlet, Return)	Area (m^2)	Percentage of Usable wall area
55-25	38.961	21%
45-25	53.385	29%
35-25	85.745	46%

Table 6-5:Area of heat emitter require for Retrofit A model in room RC 426.

RC 422		
Temperature (Inlet, Return)	Area (m^2)	Percentage of Usable wall area
55-25	8.991	15%
45-25	12.32	21%
35-25	19.787	34%

Table 6-6:Area of heat emitter require for Retrofit A model in room RC 422.

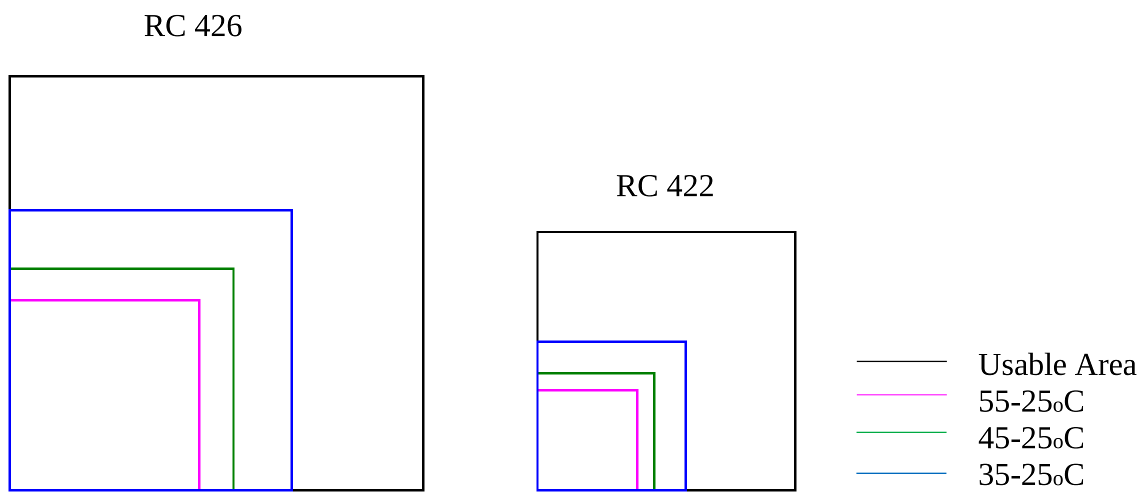

Figure 6-6:Size of emitters for each supply temperature compared to usable wall area for Retrofit A model.

Table 6-5 and 6-6 shows the emitter size for varying supply temperatures and illustrated on Figure 6-5. Supply temperature of 35oC for both rooms are larger than the usable wall area which is the same as was calculated for the Calibrated model. Both the 55 and

45oC have decreased in size as expected however they are still impractical as the 55oC still would take 53% of usable wall space in RC 426 and 50% in RC 422.

6.3 Retrofit B

The Retrofit B model introduced internal wall with board insulation and the insulated floors where there was an air gap, full construction details of the material can be seen on Table 5-3.

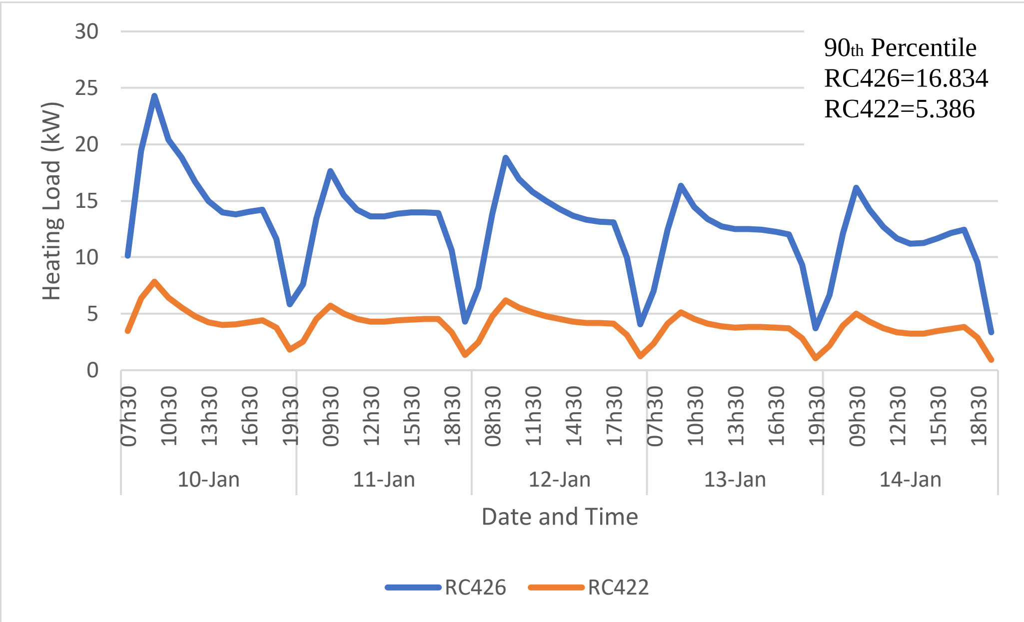

Figure 6-7: Heating capacity for Retrofit B model.

The Heating load for Retrofit B model can be seen on Figure 6-7. The heating load again has been decreased in general, which again has seen the 90th percentile value decrease to 16.834 and 5.386 for RC426 and 422 respectively. The maximum load on the room RC426 has again decreased to below 25kW. The overall pattern remains the same except for the midday dip in the Friday for both zones, where the load increases from 13:30 to 18:30. Daily peaks for zone RC422 is below 5kW for 3 of the 5 days.

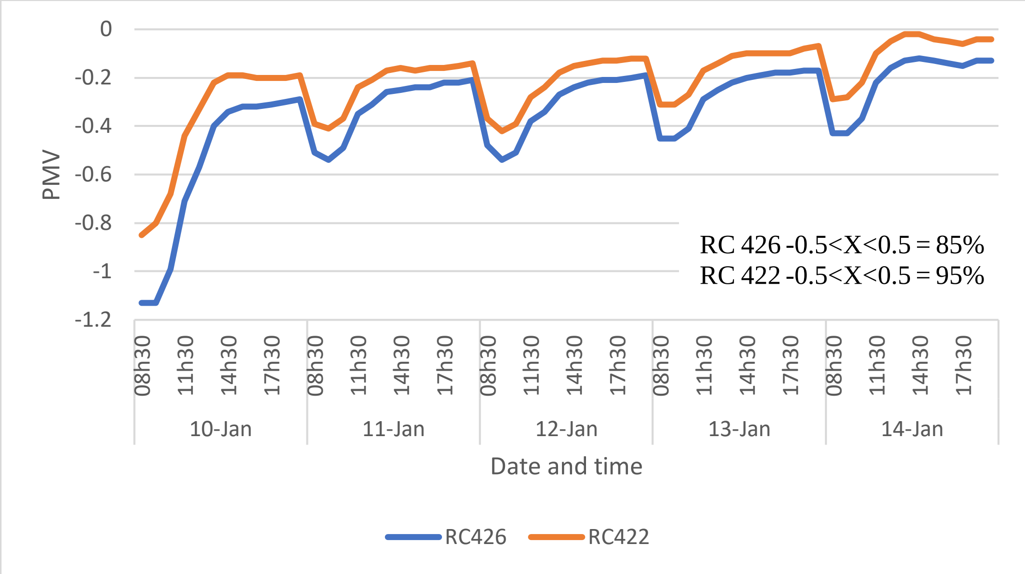

Figure 6-8: Thermal comfort for Retrofit B model.

Figure 6-8 illustrates the thermal comfort for Retrofit B with the heating capacities 16.9 and 5.4kW. Unlike what was seen for retrofit A both zones have seen increase in thermal comfort, increasing to 85 from 73% for RC426 and 95 from 93 for RC422. Again, the thermal comfort mirrors what can be seen in the heating capacity with the minimums still appearing in the Monday morning. It can be noted that the 9:30 reading for RC426 is now equal to that of 8:30 rather than less which was seen on retrofit A.

Zone	Energy Delivered (kWh)	Energy per m2	Energy saved compared to Calibrated model (%)
RC426	22211.2	73.16	19.26
RC422	5706.2	51.76	23.49
Total	27917.4	67.5	20.19

Table 6-7:Energy delivered to Retrofit B model to rooms and the savings made from last model.

Table 6-7 shows the energy delivered to the Retrofit B model. As oppose to what was seen in the energy savings from Retrofit A the majority of the savings % can be seen in RC426 for the same reason that saw RC422 benefit more from retrofit A in that theRC426 was more internal wall and RC422 has more external. With the retrofit packages A and B combined the total energy consumption on the model has been reduced by over a 5th.

RC 426		
Temperature (Inlet, Return)	Area (m_2)	Percentage of Usable wall area
55-25	34.465	18%
45-25	47.226	25%
35-25	75.851	40%

Table 6-8:Area of heat emitter require for Retrofit B model in room RC 426.

RC 422		
Temperature (Inlet, Return)	Area (m_2)	Percentage of Usable wall area
55-25	7.193	15%
45-25	9.856	21%
35-25	15.83	33%

Table 6-9: Area of Heat emitter for Retrofit B model in RC 422.

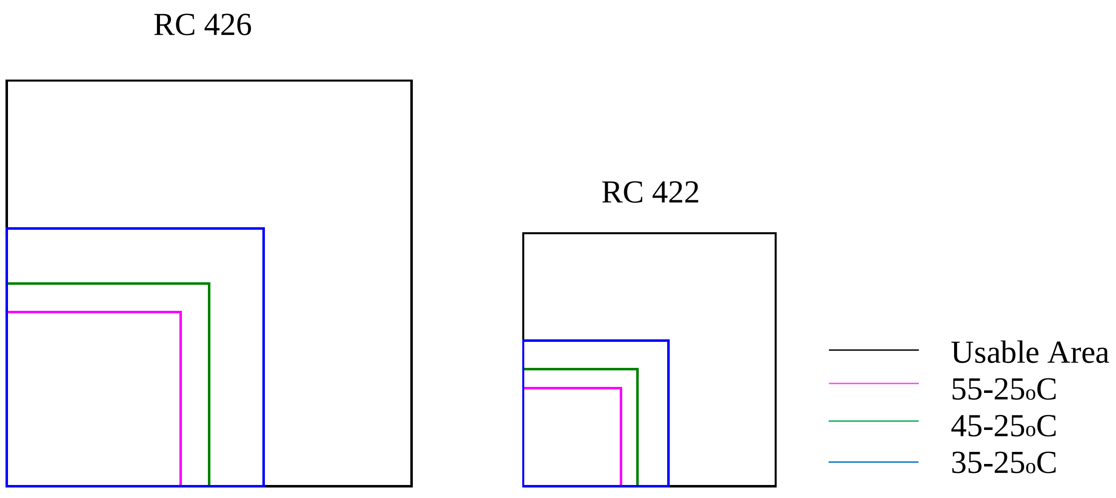

Figure 6-9:Size of emitters for each supply temperature compared to usable wall area for Retrofit B model.

Table 6-8 and 6-9 show the calculated areas of the heat emitters required for the heating capacity of 16.9 and 5.4kW for RC426 and RC422 respectively. For Retrofit B the supply temperatures of 55ovc starts to become semi-feasible with the percentage of usable area of 18 and 15% for the zones. However, supply temperature below 45 and 35oC still provide impractical measurements for the usable wall area.

6.4 Retrofit C

The Retrofit C model replaced glazing going from double to triple glazing and the frames have also been upgraded to included cork insulation, full details of the construction of the materials can be seen on Table 5-4.

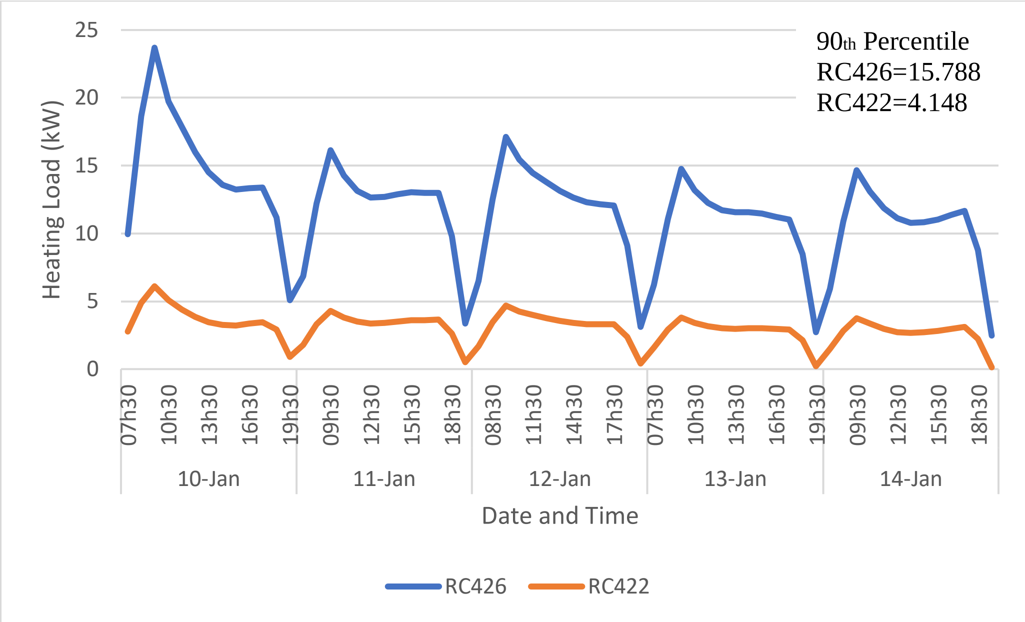

Figure 6-10: Heating capacity for Retrofit C model.

The Heating load for Retrofit B model can be seen on Figure 6-7. The daily peak loads on the room RC426 have seen a decrease that even sees the dates 13th and 14th below 15kW and also below 5kW for 11th to 14th. RC422 also sees a dip in the daily troughs with the reading at 19:30 on the 14th only being 0.13kW. The heating load again has been decreased in general that again has seen the 90th percentile value decrease to 15.788 and 4.148 for RC426 and 422 respectively.

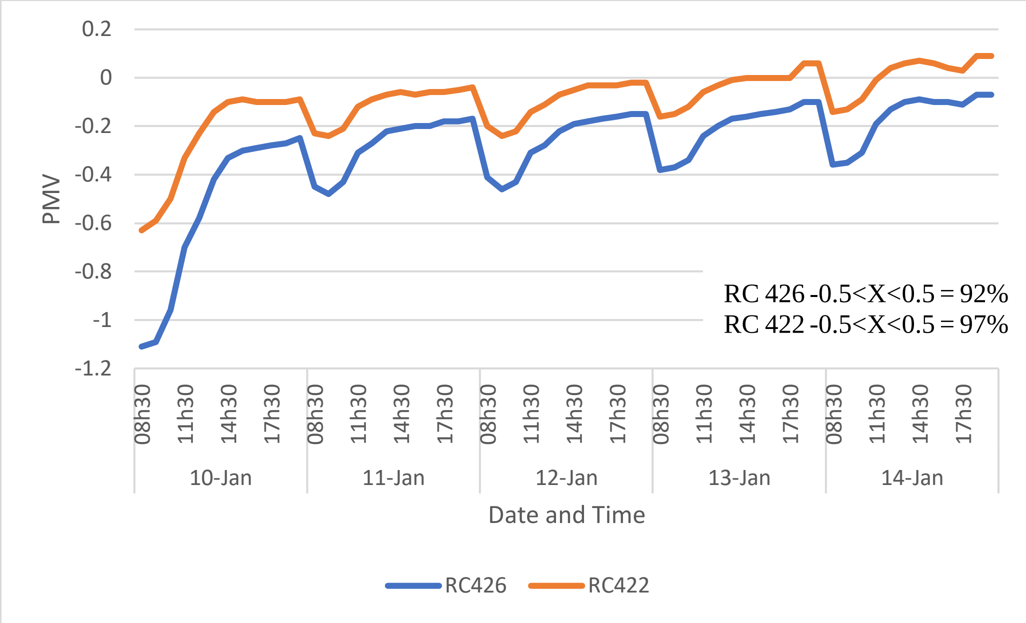

Figure 6-11: Thermal comfort for Retrofit C model.

Figure 6-11 illustrates the thermal comfort for Retrofit C with the heating capacities calculated above. Both zones have seen further improvement of thermal comfort with RC422 nearing 100% and RC426 over 90%. What is interesting to note the retrofit C model gives the first positive values that can be observed in RC 422 on the 13th for the last to measure hours and on the 14th for all points after 11:30.

Zone	Energy Delivered (kWh)	Energy per m^2	Energy saved compared to Calibrated model (%)
RC426	20877.94	68.77	24.10
RC422	4122.92	37.4	44.72
Total	25000.9	60.4	28.5

Table 6-10: Energy delivered to Retrofit C and savings made from Calibrated model.

Table 6-7 shows the energy delivered to the Retrofit C model. The savings for RC422 has increased by over 20% when compared with Retrofit B and in total almost 45%. The overall energy saving in the model has decreased by more than a quarter, 28.5%, when compared to the Calibrated model. This also sees the energy per m^2 in that room drop to 60.4 kWh/m^2 which if consistent throughout the building would relate to an EPC rating of B.

RC 426		
Temperature (Inlet, Return)	Area (m^2)	Percentage of Usable wall area
55-25	23.976	17%
45-25	32.853	23%
35-25	52.766	38%

Table 6-11:Area of heat emitter require for Retrofit C model in room RC 426.

RC 422		
Temperature (Inlet, Return)	Area (m^2)	Percentage of Usable wall area
55-25	4.795	12%
45-25	6.571	16%
35-25	10.553	26%

Table 6-12:Area of heat emitter require for Retrofit C model in room RC 422.

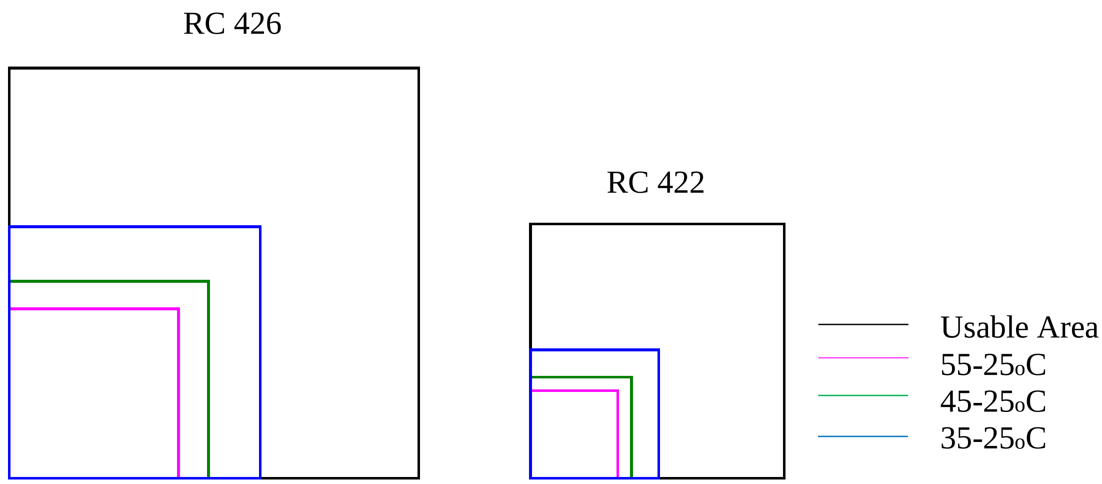

Figure 6-12:Size of emitters for each supply temperature compared to usable wall area for Retrofit C model.

Table 6-11 and 6-12 show the calculated areas of the heat emitters required for the heating capacity of 15.8 and 4.2kW for RC426 and RC422 respectively. These sizes are highlighted in Figure 6-12 where they are compared to usable area for the respective zones. As there was little reduction in the heating capacity of RC426 consequently there has been little improvement of the area that the emitter uses for the varying supply temperature. However, as 23.97m2 of the ceiling is being used 55oC for and even the 45oC value of 32.85m2 are feasible. The emitter sizing for RC422 for the 55oC is again very practical but the 45oC would provide difficult implemented.

6.5 Results Summary

The results of the above simulations that have been summarised to compare a draw conclusion of the energy savings made that can result in the reduction for heat capacity and the thermal comfort and the area of the emitters for the corresponding supply temperatures.

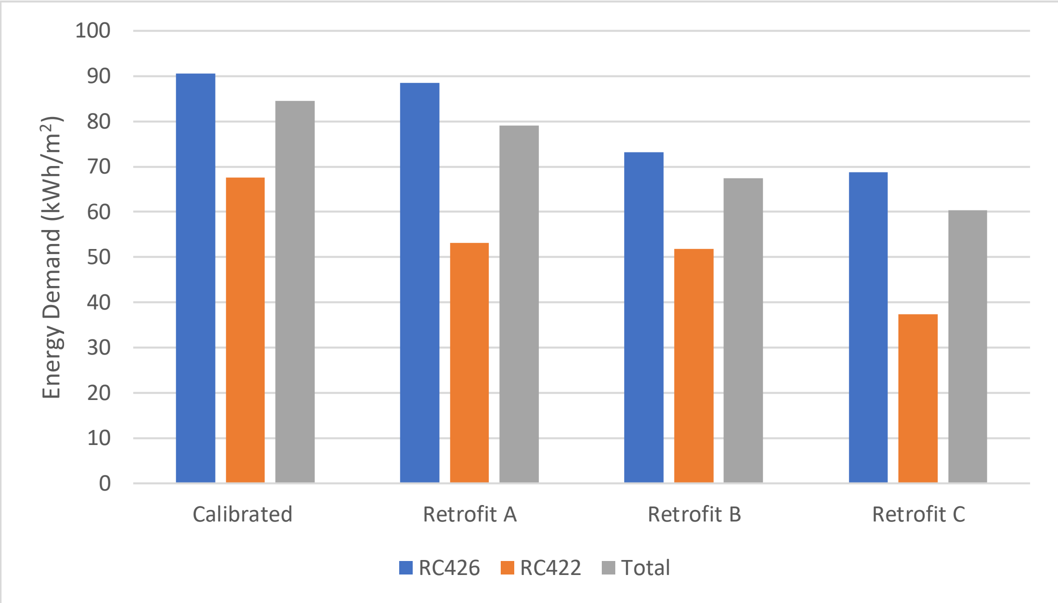

Figure 6-13: Energy Demand of each zone per area for each retrofit.

Figure 6-13 illustrates the energy consumption per floor area for each zone and combination of both. It can be observed that the main reductions in energy demand for RC426 was during retrofit package B and C. Although the most majority of rooms in the Royal College are similar in size to the RC422, the majority of them have three internal walls thus would see similar reduction per floor area when implementing these changes to the internal walls in the Royal College. RC422 was the main benefactor of retrofit A (the insulation of the external walls and ceiling) as there was minimum change in RC426 it can be gathered that the external wall not the ceiling was accountable for the majority of difference due to RC422 having more external wall per floor area and also due to the ceiling and floors being connected to similar zones with

0_oC temperature drop off . The improvement of the thermal properties of the external walls came from filling of the air gap, if a material analysis was conducted and no gap was found it would be more difficult to achieve the same amount of savings with solid walls. For RC426 the majority of the savings were found in insulating the internal walls, although the majority of the rooms in the Royal College are more sized like RC422 most of them do have 3 internal walls so Retrofit B package is most applicable to the area. Additionally, there are problems due to the Royal College being a listed A building by historic Scotland, therefore, changes that can be made may be restricted, but as previously mentioned there was recently improvements made to the Royal college after the EPC rating was completed in 2009 so there is hope that these changes may also be accepted. However, the methodology and many factors that go into these decisions is not clearly available to the general public, hence it would be a questionable issue to be put forward to the local council. As was mentioned in section 6.1 this building was chosen due to the high intensity of energy. Nonetheless, the building still fell below the energy benchmarks set out by CIBSE, but these benchmarks have been criticised as being too lenient so the just because it's below this benchmark does not conclude that the original building is in any way sustainable. With the improvements the building section would achieve an EPC rating of B from Retrofit B model onwards.

Zone	Calibrated (%)	Retrofit A (%)	Retrofit B (%)	Retrofit C (%)
RC426	75	73	85	92
RC422	93	93	95	97

Table 6-13:Thermal comfort, percentage of PMV between -0.5 and 0.5.

Table 6-13 shows the percentage of hours that meet the set-out requirements for thermal comfort of the PMV being between -0.5 and 0.5. A fear of reducing the heating capacity for retrofits is that it sacrifices the thermal comfort of the users of the buildings especially when the 90_{th} percentile of the heating load of a week is used however it can be seen that with exception to the RC426 in the Retrofit A where thermal comfort was reduced by 2%. For example, RC426 thermal comfort improved by 10 and 17% for Retrofit B and C. RC422 already had a very high value for thermal comfort however this is improved upon still by 2% and 45 for Retrofit B and C.

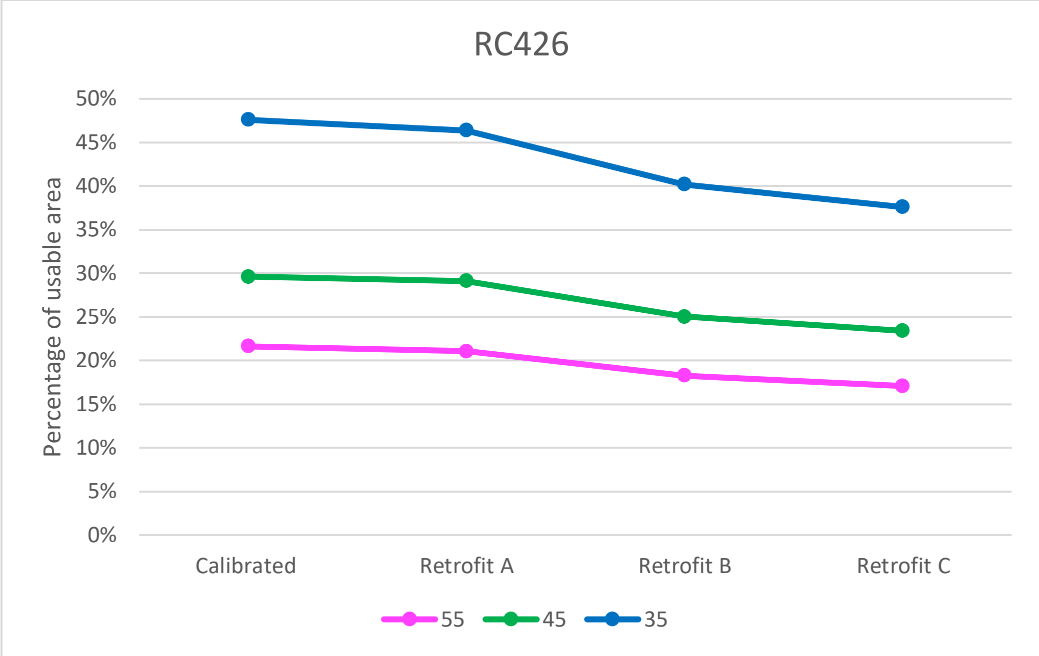

Figure 6-14: Percentage of heat emitter per usable area for each model for varying supply temperatures.

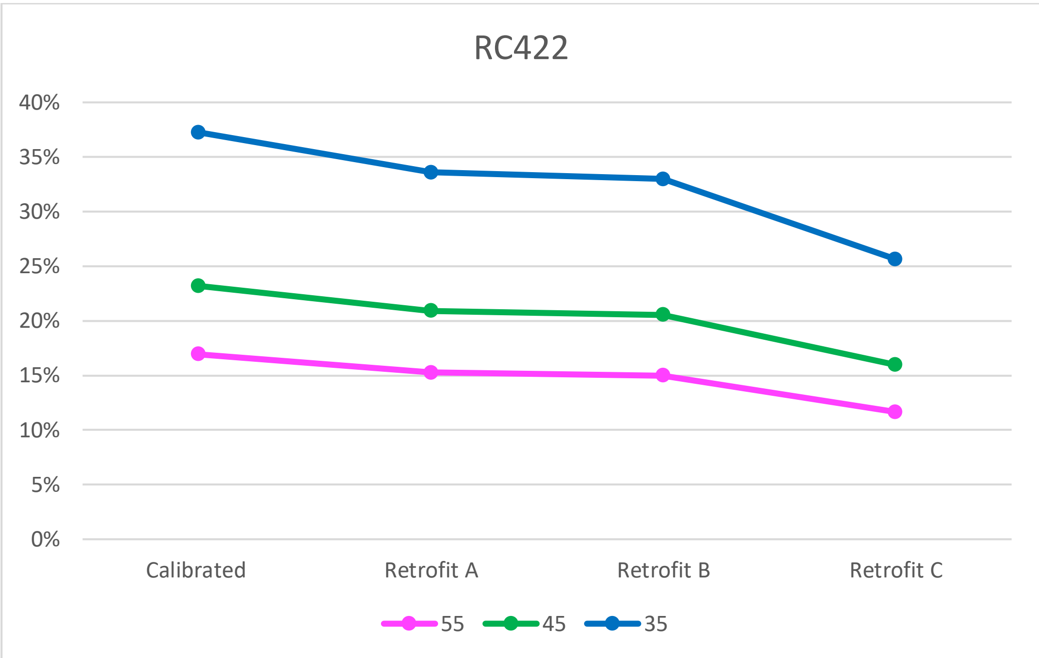

Figure 6-15: Percentage of heat emitter per usable area for each model for varying supply temperatures.

Figure 6-14 and 6-15 show the areas of the heat emitters for the varying supply temperature for each of the retrofit packages for the respective zones. It was determined that the maximum percentage of usable area that a heat emitter could use is 20%. For the supply temperature of 35$_o$C the minimum value was 38% and 26% for RC426 and RC422 therefore cannot be considered further. The 20% value was achieved for both zones by only the 55$_o$C supply temperature; 45$_o$C narrowly misses out as the cut off for RC426 by 3% for Retrofit C. Heat emitter percentage reached below 20% for both zones with the supply temperature of 55$_o$C from Retrofit B. So, it can be concluded that the triple glazing with passive house standard insulated frames are not necessary for low temperature heating within the Royal College for the modelled zones. A factor that is also restricting the area of the heat emitter is the heating set point of 22$_o$C, as previously mentioned it is common for residential DHN in Denmark to include an incentive for lower setpoints thus allowing the return temperature to be lower and in turn decreasing the required area for the heating capacity and improving the general efficiency of the overall system (Tunzi *et al.*, 2018). However, due to the fact that this is a non-domestic system there is a more limited scope to employ a similar function as it is imperative that the university provides an environment that is thermally comfortable for a range of students from different backgrounds to learn in.

7 Economic Analysis

To assess whether or not the retrofit packages simulated in Chapter 6 are economically viable the payback period and the net present value (NPV) were calculated for each package. The equations used to calculate the values can be seen below. The below calculations are only an analysis of the retrofits themselves and does not include the analysis of the heat pump systems as they would be present in any 5th generation systems that would be implemented.

$$Payback\ period = \frac{Cost\ of\ Asset}{cash\ inflows} \quad (12)$$

$$NPV = \sum \left(\frac{CF_n}{(1+i)^n}\right) - inital\ investment \quad (13)$$

For the NPV equation CF_n is the cash flow in the nth period which for this equation is 30 years which is also used for n, i is the discount rate and due to the cost of after installation being negligible for this study the cost of assets and initial investment are the same figure this case can be seen on Table 6-1. Cash inflows will be represented by the annual savings made on thermal energy which for the case of the 5GDHN would be electrical energy. The cost of energy was gauged from the UK government BEIS department that publish the prices paid by Non-domestic consumers, In this document the University of Strathclyde with a 5GDHN would be considered an “Extra Large” consumer and the last report was from Q1 in 2020 where the price of electricity including the climate change levy was 12.48p/kWh, price variation on electricity price is out with the scope for the economic analysis (BEIS, 2020). The cost of retrofits beyond the initial installation of them are also deemed negligible, which is common for cost benefit analysis of retrofits packages in the built environment (Booth and Choudhary, 2013). The period that the retrofits will be judged upon over 30 years the life cycle (Chen *et al.*, 2020). Discount rate of 3% is also assumed for the NPV calculations.

Material	Cost (£/m2)	Area (m2)
External Wall Insulation	35	126.9
Ceiling Insulation	50	413.85
Internal Wall Insulation	17.50	282.4
Floor Insulation	25	413.85
Triple Glazed Windows	400	67.5

Table 7-1: Cost of retrofits per m2

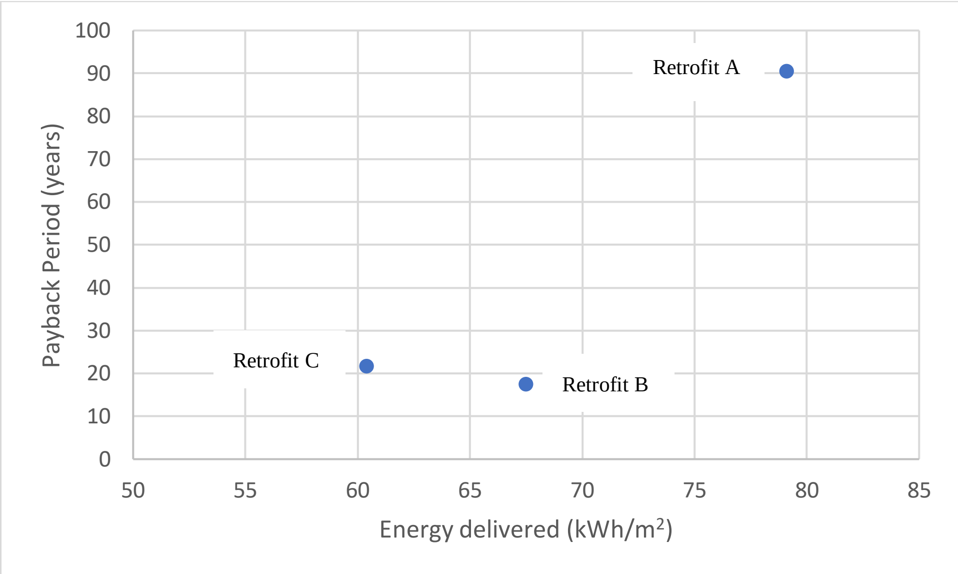

Figure 7-1: payback periods in respect to energy demand of model.

Figure 7-1 shows the Retrofit model payback periods with the energy demand of that model. The lowest of payback period of all the models is Retrofit B with the value 17.4 years. The surprising figure of the payback period analysis is that Retrofit A would take more than 90 years to make up for the initial investment for the insulation of the exterior wall and ceiling insulation which can conclude that this retrofit alone is unjustifiable from an economic standpoint. Interestingly as well that adding the improved glazing that reduces the energy demand causes the payback period to increase this is due to the rather substantial amount of money that the improvements costs. Similar large values for passive retrofits for pay back periods have been found in previous studies however what is usually seen that the fitting of triple glazing reduces the payback period (Chen *et al.*, 2020) (Ciulla, Galatioto and Ricciu, 2016). However, this may be due to the size and dimensions that are used in the Royal College which is typical for buildings constructed in that era the height being 2.5m was taken into consideration when creating the cost of retrofit tables.

	Retrofit A	Retrofit B	Retrofit C
NPV	-25041.4	-14995.03	-26585.46

Table 7-2: NPV for each case of Retrofit case

Table 7-2 shows the NPV values for each retrofit model. As can be observed from the table each value is extremely negative for a lifecycle of 30 years. Although negative NPV values do not necessarily mean that the investment is should not be made negative values of this magnitude should be a cause for concern as the NPV is considered the best tool for judging retrofits as it is the “only tool that takes into considers the stakeholders objectives of maximising the return on investment.” (Menassa, 2011). What is reflected in these results similarly to the payback period results is that the investment gets less lucrative when adding the triple glazing going from Retrofit B model to C. Negative NPV values were also found when upgrading glazing in retrofit analysis of the UK housing stock however this was consider single to double and not double to triple (Booth and Choudhary, 2013). A large contributing factor of the negative values for NPV is the static nature of the cost of energy for used for this analysis as electricity prices have been rising rapidly since the 2007which has saw the price more than double for extra-large consumers from 5.26 to 12.48 p/kWh in 2019. Ultimately the same could be said for all of the values used for this limited economical study as even the price of retrofit materials is hard to grasp solid figures as prices vary wildly depending on a number of factors including materials used and the size of project that can introduce discounts other than discount factor used. The same can be said again for the discount factor used which is not easily determined and is usually a variable that is studied in economic analysis for the built environment. As limited as the economic analysis is there as there is still no clear methodology to fully evaluate building retrofits simply due to sheer amount of variable (Zheng and Lai, 2018).

8 Conclusion

The aim of this thesis was to analysis the current demand that is on the DHN at the university of Strathclyde, and analyse the surrounding area that would allow for the DHN to be able to contribute to a 5GDHCN. A section of a building that is connected to the DHN at the university was modelled to implement retrofits to reduce the demand so that ultra-low supply temperatures could be utilised in the building

8.1 Key Findings

Resource Assessment

The first key finding of the study to the potential of upgrading the current DHN to a 5th generation system at the university of Strathclyde is a issue within the built environment in Urban areas; that there is that there is a lack of space for storage. This aspect of a 5GDHCN is key as it for manipulating peak demands, allowing for manipulation of electricity tariffs and for taking advantage of waste heat during the summer months when it is not needed, this threat of lack of space for storage is well known and was identified by varies previous studies (Lund *et al.*, 2014)(Buffa *et al.*, 2019). Ultimately this is due to the size of the DHN in the city centre as space in the outskirts of the city are too far away would have excessive pumping costs and monumental cost for digging up of the ground to lay the pipes therefore would not be justifiable.

As stated the 5GDHCN utilise heat pumps to upgrade heat sources and the river Clyde, although already used as a source for a residential DHN, was shown in the feasibility study done using steps provided by CIBSE to have more than enough potential to supply a heat pump that would be able to be the main heat production.

Model Results

Through improving the model created by upgrading the thermal properties of the materials is was discovered that demand could be reduced by more than a fifth to 60.4 kWh/m^2. If these improvements were to be replicated through the building it would improve the Royal college to an EPC rating of B.

It was deemed that the lowest supply temperature that would be possible for the Royal College was 55$_{o}$C. However triple glazing would not have to be installed for this low temperature to be utilised in both zone heat emitters. This would be able to be implemented without sacrificing thermal comfort. The redundancy of triple glazing was also shown in the economic analysis where it increases payback period and decreased NPV.

8.2 Limitations

Due to the wide scope of district heating networks it was impossible to tackle every aspect of them in the timeframe given for the thesis, thus there are multiple limitations within this study.

Due to the nature of the thesis it was impossible to conduct feasibility studies for all of the appropriate resources in any great detail and served mainly as an outline for technologies for a concept system at the University of Strathclyde.

Only a small section of one of the 19 buildings connected to the DHN was modelled, thus the saving that was achieved for this model is most likely not going to be possible for the majority of the buildings connected. Furthermore, the heating capacity and thermal comfort was only based on one week's data this would need to be expanded on to ensure that the decrease in heating capacity is viable. Calibration of the model was also conducted using the energy supplied to the heat plate exchanges before the heat is transferred down to 73$_{o}$C to be used which is a massive oversite of this section.

Only passive retrofit measures were considered for the model, but there several other measure that could be implemented such as editing the heating schedule for extending the hours that could be implemented to counteract the slower reaction time that lower heat capacities will have, set -point manipulation however has limited scope due to regulations and the need to provide the best environment to learn in.

The sizing of the heat emitters also only uses Fourier's law is extremely limited as it only focuses on the conductivity aspect of the emitter. A more accurate methodology requires multiple transient thermal energy equations to be solved however was out with the scope for this thesis. (Teskeredzic and Blazevic, 2018).

Economic analysis is also heavily limited in capacity to truly evaluate the potential of 5GDHN due to the static nature of the figures used such as the prices for the retrofits and the price of energy consumed. Also, it was noted that the COP efficiency of heat pumps being used was not taken into consideration for energy prices.

8.3 Future Works

As mentioned at the begging of the thesis the main focus was on heating element of 5GDHCN. There should be a further study into a feasibility of the cooling element of a potential 5GDHCN and the work that would be required as currently this is not served by the DHN at the University of Strathclyde.

Hourly measured data for calibration to ASHRAE standards would give the calibrated model much more weight and give a better analysis of a baseline to calculate potential energy savings from improving thermal properties of the building material. Another element that could be further studied is analysis of the materials in particular the exterior wall that are actually used in the Royal College itself so that the model can reflect that for the calibrated model.

The resource assessment was conducted to only consider resources within 1km however there is no methodology to balance the pumping and digging cost against the energy that the resource could provide a methodology like this would streamline the planning process of district heating and cooling networks.

Furthermore, it was assumed that from the supply temperature of 25oC was upgraded by heat pump in substations located in each building analysis on the performance of these booster heat-pumps and their economic capabilities against using immersion heaters for this case study should be studied. Additionally, recently heat-pumps has seen improvements in outlet temperatures of up to 70_oC this should be analysed to see if the trade off in COP is worth the savings in retrofits that would no longer be required due to the increase in supply temperature.

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Appendices

Appendix A

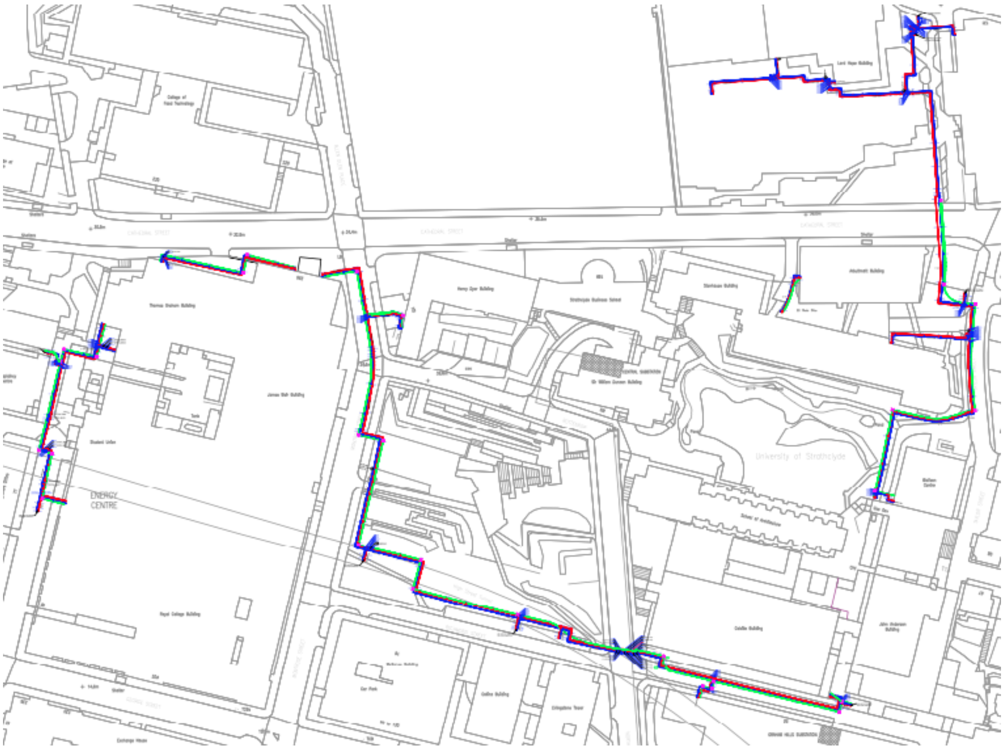


Figure 0-1: DHN Main Layout

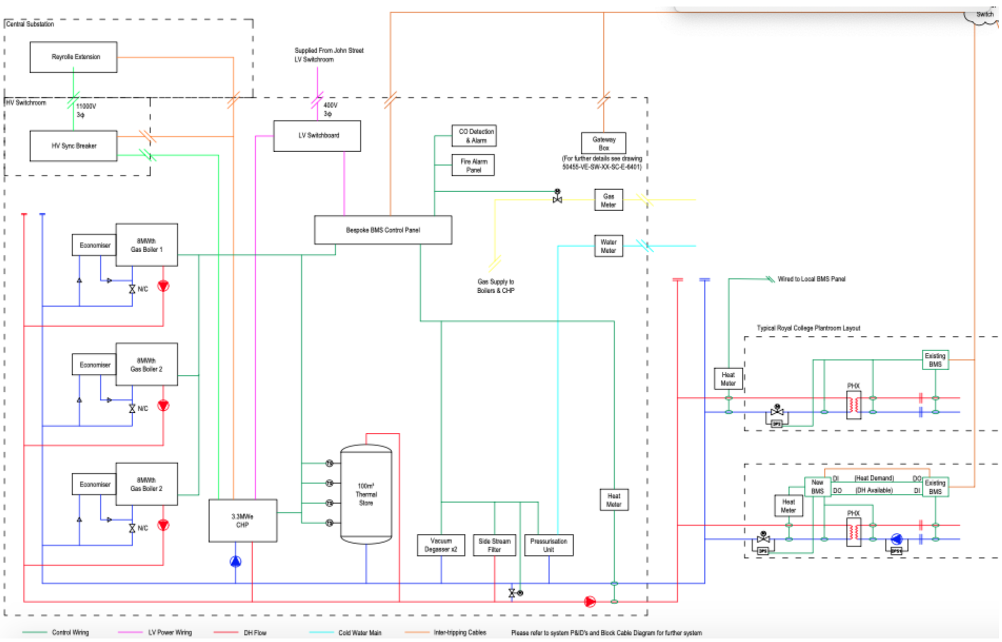
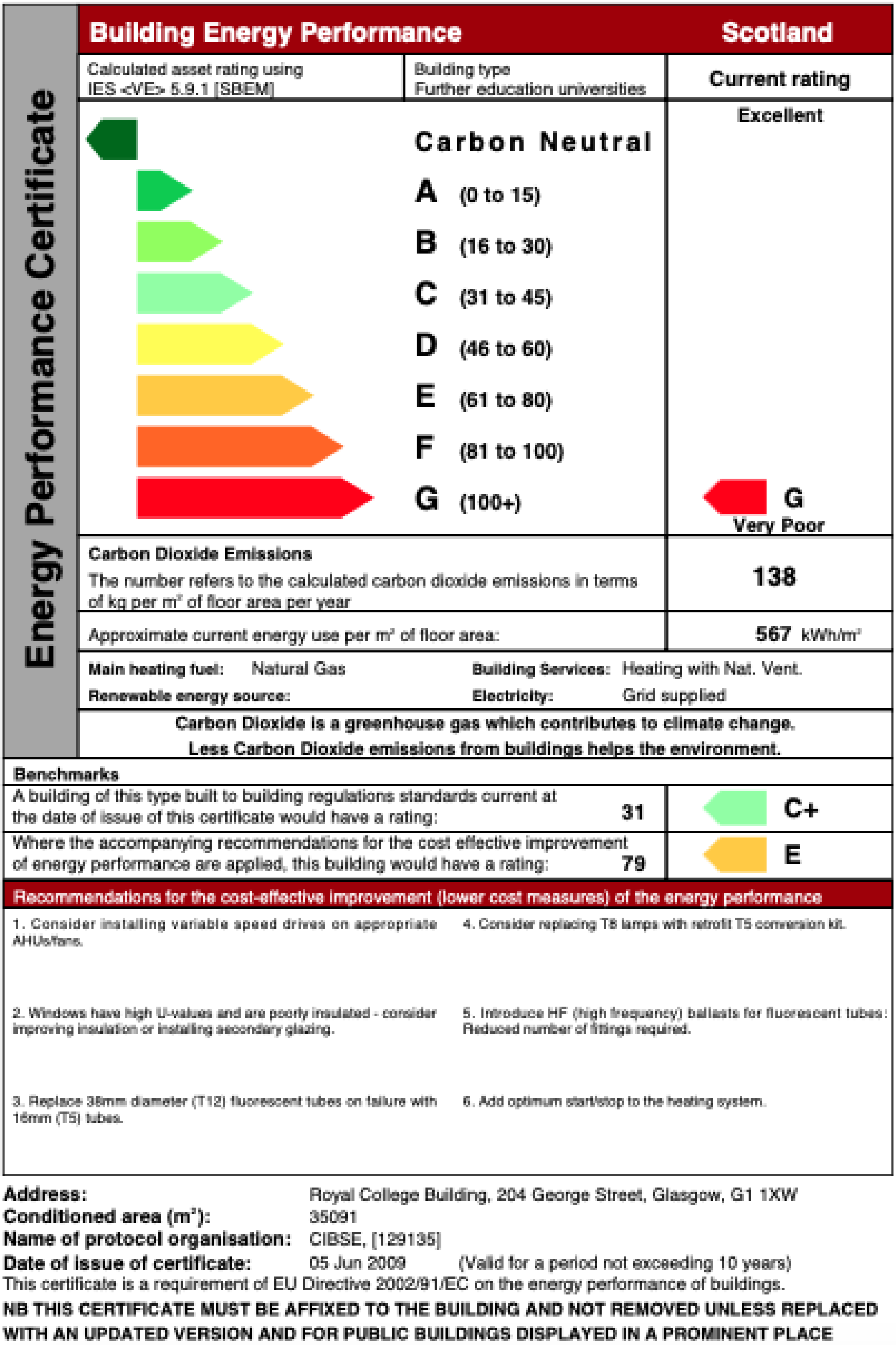


Figure 0-2:Architectural system drawing.

Appendix B



Energy Performance Certificate

Building Energy Performance | **Scotland**

Calculated asset rating using IES <VE> 5.9.1 [SBEM]	Building type Further education universities	**Current rating**

Rating	Band	Current rating
Carbon Neutral		Excellent
A	(0 to 15)	
B	(16 to 30)	
C	(31 to 45)	
D	(46 to 60)	
E	(61 to 80)	
F	(81 to 100)	
G	(100+)	G Very Poor

Carbon Dioxide Emissions The number refers to the calculated carbon dioxide emissions in terms of kg per m² of floor area per year	138
Approximate current energy use per m² of floor area:	567 kWh/m²

Main heating fuel: Natural Gas **Building Services:** Heating with Nat. Vent.
Renewable energy source: **Electricity:** Grid supplied

Carbon Dioxide is a greenhouse gas which contributes to climate change.
Less Carbon Dioxide emissions from buildings helps the environment.

Benchmarks

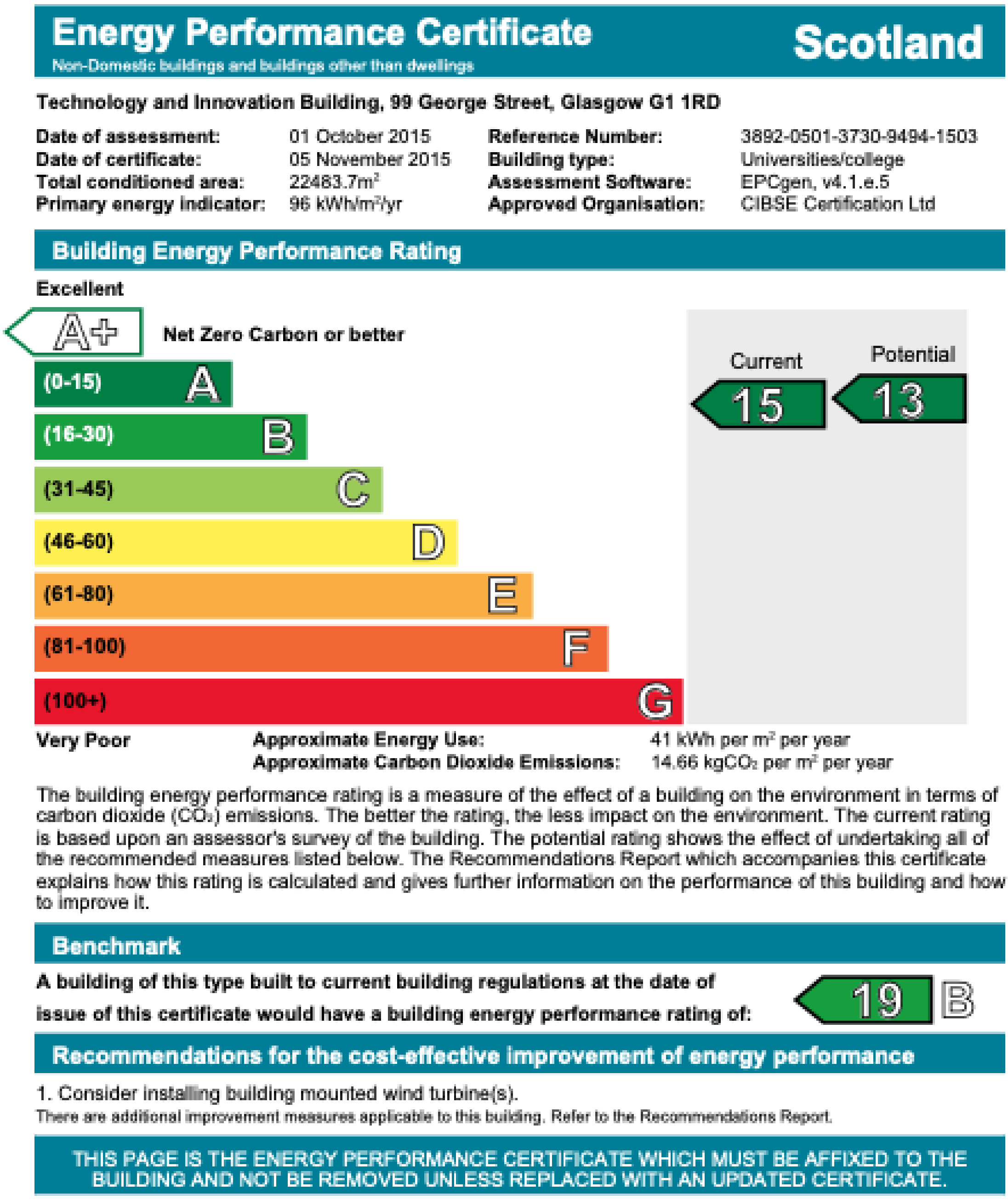
A building of this type built to building regulations standards current at the date of issue of this certificate would have a rating:	31	C+
Where the accompanying recommendations for the cost effective improvement of energy performance are applied, this building would have a rating:	79	E

Recommendations for the cost-effective improvement (lower cost measures) of the energy performance

1. Consider installing variable speed drives on appropriate AHUs/fans.
2. Windows have high U-values and are poorly insulated - consider improving insulation or installing secondary glazing.
3. Replace 38mm diameter (T12) fluorescent tubes on failure with 16mm (T5) tubes.
4. Consider replacing T8 lamps with retrofit T5 conversion kit.
5. Introduce HF (high frequency) ballasts for fluorescent tubes: Reduced number of fittings required.
6. Add optimum start/stop to the heating system.

Address: Royal College Building, 204 George Street, Glasgow, G1 1XW
Conditioned area (m²): 35091
Name of protocol organisation: CIBSE, [129135]
Date of issue of certificate: 05 Jun 2009 (Valid for a period not exceeding 10 years)
This certificate is a requirement of EU Directive 2002/91/EC on the energy performance of buildings.
NB THIS CERTIFICATE MUST BE AFFIXED TO THE BUILDING AND NOT REMOVED UNLESS REPLACED WITH AN UPDATED VERSION AND FOR PUBLIC BUILDINGS DISPLAYED IN A PROMINENT PLACE

Figure 0-3: EPC rating of Royal College.



Energy Performance Certificate — Non-Domestic buildings and buildings other than dwellings — **Scotland**

Technology and Innovation Building, 99 George Street, Glasgow G1 1RD

Date of assessment:	01 October 2015	**Reference Number:**	3892-0501-3730-9494-1503
Date of certificate:	05 November 2015	**Building type:**	Universities/college
Total conditioned area:	22483.7m²	**Assessment Software:**	EPCgen, v4.1.e.5
Primary energy indicator:	96 kWh/m²/yr	**Approved Organisation:**	CIBSE Certification Ltd

Building Energy Performance Rating

Approximate Energy Use: 41 kWh per m² per year
Approximate Carbon Dioxide Emissions: 14.66 $kgCO_2$ per m² per year

The building energy performance rating is a measure of the effect of a building on the environment in terms of carbon dioxide (CO_2) emissions. The better the rating, the less impact on the environment. The current rating is based upon an assessor's survey of the building. The potential rating shows the effect of undertaking all of the recommended measures listed below. The Recommendations Report which accompanies this certificate explains how this rating is calculated and gives further information on the performance of this building and how to improve it.

Benchmark

A building of this type built to current building regulations at the date of issue of this certificate would have a building energy performance rating of: 19 B

Recommendations for the cost-effective improvement of energy performance

1. Consider installing building mounted wind turbine(s).

There are additional improvement measures applicable to this building. Refer to the Recommendations Report.

THIS PAGE IS THE ENERGY PERFORMANCE CERTIFICATE WHICH MUST BE AFFIXED TO THE BUILDING AND NOT BE REMOVED UNLESS REPLACED WITH AN UPDATED CERTIFICATE.

Figure 0-4: EPC rating of TIC Building