Department of Mechanical and Aerospace Engineering

Investigating Opportunities for Low Impact Energy Retrofitting in Cities

Author: Fraser Muir Reid

Supervisor: Professor Joseph Clarke

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Abstract

Currently, 24% of Scottish residents live in tenements, almost all of which are heated using gas, a non-sustainable or low-carbon option. A worldwide trend of integrating heat networks and sustainable heat technologies is currently taking place. Swapping to a low temperature, sustainable heat supply is often coupled with complete infrastructure change. The aim of this study is to evaluate the feasibility of directly implementing heat pumps into current heating systems, whilst avoiding re-infrastructure.

A method was established to address the issue of non-invasive heat pump integration within domestic archetypes. This study focuses on tenement flats as they make up the largest percentage of occupied dwellings in Scotland, as well as posing as an arduous housing type to retrofit.

A review of literature surrounding Scottish housing, district heating and low temperature heat sources provides context for the project study. Modelling of a standard tenement flat was facilitated using the energy performance simulation software, ESP-r. The model created had appropriate energy ratings, insulation qualities, building materials as well as operational details. The thermal environment of the model under a base case, medium temperature and low temperature heating system were simulated. Results were evaluated on two significant criteria; unmet heating hours and energy consumption.

The results highlighted that without any refurbishment a low temperature heat pump could not meet 50% of all heating hours within a year. With basic retrofits and improvements these results decreased to 10%. The low temperature heat pump was deemed not feasible due to its inability to meet all heating hours even after intrusive measures were taken. The integration of a medium temperature heat pump however, gave rise to 300 unmet heating hours (6%) across an entire year, and after some simple control alterations, this was reduced to only 2 unacceptable unmet heating hours. Without retrofit or refurbishment, the medium temperature heat pump can therefore be considered feasible. The promising results emerging from this project give rise to the possibility of future work related to different building archetypes.

Acknowledgments

Firstly, I would like to extend my greatest thanks and appreciation to my project supervisor, Professor Joe Clarke, for inspiring me to do better, guiding me through this project step by step and helping me produce a concise, consistent and coherent project.

A massive thank you to Carmina Bocanegra, the ESP-r guru, for putting up with my endless list of questions and requests for help during the modelling phase of this study.

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I would also like to commend the Glasgow weather, not just for its contribution within the context of this project but also for continuing in characteristic vein, keeping me at my desk and my focus orientated towards this project.

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Nomenclature

A	
AC/h	Air changes per hours
C	
CO_2	Carbon dioxide
G	
GWh	Energy (giga-watt hours)
K	
KWh	Energy (kilo-watt hours)
kWh/ year	Kilo-watt hours per year
M	
$MtCO_2e$	Millions of tonnes of carbon dioxide equivalent
MW	Power (mega watts)
MWe	Power (mega-watt equivalent)
MWh	Energy (mega-watt hours)
Q	
Q_H	High heat
Q_L	Low heat
T	
T_H	High temperature (K)
T_L	Low temperature (K)
ΔT	Temperature difference between radiator (mean) & air
tCO_2	Tonnes of carbon dioxide
U	
Unmet heating hours	No. of hours to not attain max heating set point in 1 year

W

W/m^2K	Thermal transmittance (watts per metre squared kelvin)
W	Work done on heat pump

List of Acronyms

ATES – Aquifer Thermal Energy Storage

BTS – Below Tolerable Standard

CHP – Combined Heat and Power

COP – Coefficient of Performance

DER – Dwelling Emission Rate

DHW – Domestic Hot Water

EER – Energy Efficiency Ratings

EIR – Environmental Impact Rating

EPC – Energy Performance Certificate

EU – European Union

FEE – Fabric Energy Efficiency

GSHP – Ground Source Heat Pump

NHBC – National House Building Council

SAP – Standard Assessment Procedure

WSHP – Water Source Heat Pump

Chapter 1. Problem Background

The rationale for this project came from the need to identify and encourage methods of non-intrusive and inexpensive alternatives to heat residential buildings using low temperature heat supply, focussing on Glasgow, Scotland.

1.1. Energy Usage

World energy consumption is growing, and with it so are carbon emissions. Many measures are being established to provide sustainable, renewable and carbon-zero solutions to the ever-increasing demand for fuel. Most these measures, wind energy, solar power, tidal and wave technologies, address only one half of the energy crisis; electricity. The other half of this crisis is heating. Buildings consume just under 40% of the world's total energy demand. They are responsible for roughly 33% of the greenhouse gas emissions, which is almost entirely carbon based (Chau, et al., 2015).

With economic growth driving urbanisation in most areas of the world, developing and developed, it is understandable that innovative technologies and design advances are necessary to achieve energy sustainability (World Energy Council, 2016). A major contribution to addressing the energy crisis, and specifically heat demand, would be energy savings and reduced heating demand in buildings. However, with the projected expansion of the built environment teamed with the desire and requirement for better indoor quality the demand for energy will only rise.

In Scotland alone, heat is the biggest influence on the energy sector at around 55% of total consumption. It is therefore, not surprisingly, the largest contributor to emissions (47%). Of the energy spent on heat, 42% of it is used on domestic heating, Figure 1.1 shows the breakdown of how this heat is utilised. 23% therefore, of all energy used in the Scotland facilitates heating within residential buildings. Both The heat source and the quality of the building impact upon energy consumption, which in turn exacerbates the issues surrounding a low temperature heat supply, addressed in this study.

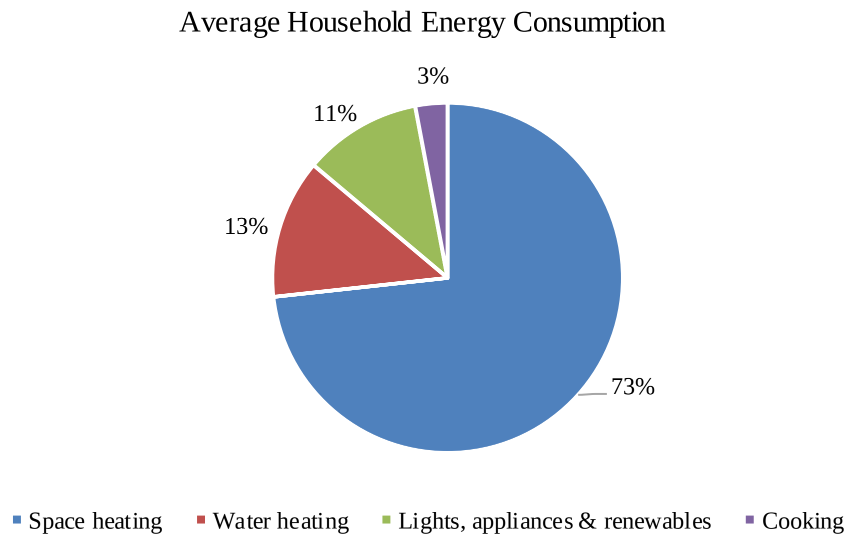

Figure 1.1. Average household energy consumption (Mueller & Palombi, 2016)

1.2. Heating Solutions

There are many solutions emerging worldwide to address the issues that this project highlights. Solutions that tackle both sides of the problem include the cleaner, greener and more sustainable energy production, as well as the reduced heating demand through retrofit and housing improvements. Both of these solutions come with downsides such as the cost of implementation and the intrusive nature of these infrastructure methods. This is especially true when looking to retrofit old, hard to treat, protected buildings such as pre-1919 tenement flats.

In the case of tenements, successful solutions might involve complete restructuring of heating systems as well as invasive methods of retrofit. However, the ability to conduct improvements in tenements with minimum disruption and intrusion would be desirable. The project considers whether low temperature heat sources, such as heat pumps, can be incorporated into current wet heating systems within these vulnerable and hard to improve dwellings without needing to alter the heating system.

There are a many projects across the globe that utilise low temperature heat sources to satisfy heat demand. Some of these schemes span entire cities and provide for hundreds of thousands of residences, however these schemes often involve extensive work being done to ensure the heat being supplied is adequate. That entails appropriate installation of the heating systems, and energy efficiency measures working hand in hand.

The technicality of these projects is constantly developing. However, that does not necessarily help with the integration within older, less energy fit homes. One of the main issues to be overcome is the cost involved in improvements to older dwellings (set against their lifespan) so that they can be adapted to using low temperature sustainable or renewable systems.

1.3. Need for Investigation

Based on the brief synopsis of the current position, including the targets set by the Scottish Government, decarbonisation of the energy sector, improved energy efficiency and establishment of district heating and communal heating schemes there is a growing need to validate alternative, low temperature forms of heating whilst avoiding intrusive and re-infrastructure demanding measures.

1.4. Aims and Objectives

This project aims to evaluate the feasibility of implementing a low temperature heat supply, for example a heat pump distributed through district heating networks, into the already existing infrastructure and heating systems in place in a variety of different building archetypes.

More specifically, the project focussed on identifying the feasible of integrating a low temperature heat source into pre-1919 tenement flats. The study highlights measures taken to increase the feasibility of integrating into already existing infrastructure. Results are achieved through modelling and simulation techniques, and extracting key data. Conclusions are then drawn based on results of unmet heating hours and energy consumption of the low temperature system compared to a fully capable, base case, system.

The objectives set out in this project are the steps taken to help achieve the aim stated above, namely:

- Highlight current condition and quality of Scottish housing stock, including energy demand statistics.

- Investigate sustainable and renewable sources that can supply low temperature heat for space heating in residential buildings.

- Create an accurate model of the targeted dwelling type, in this case a mid-terrace, two-bedroom tenement flat, on an energy performance software.

- Carry out simulations on a variety of design iterations of the model, to establish results of unmet heating hours and energy consumption as representatives for thermal comfort and cost respectively. Focussing specifically on whether a low temperature heating system can achieve the same thermal environment as a base case system.

1.5. Method

The method established identifies how the aims and objectives of the study were addressed. The aims of the study are to determine whether a district heating system, that gains heat through a low temperature heat source, like a ground source heat pump, can match the thermal comfort supplied by a single unit boiler. Key to this however, is being able to integrate the low temperature system whilst avoiding a complete re-infrastructure of the current heating systems.

To achieve the aims and objectives a project model (Figure 1.2) has been developed as a visual to represent the stages completed to reach results. The initial steps involved in planning the report and identifying the problem to be addressed included conducting an in-depth literature review to elucidate all aspects of the problem. Once initial research was finished a method could be determined.

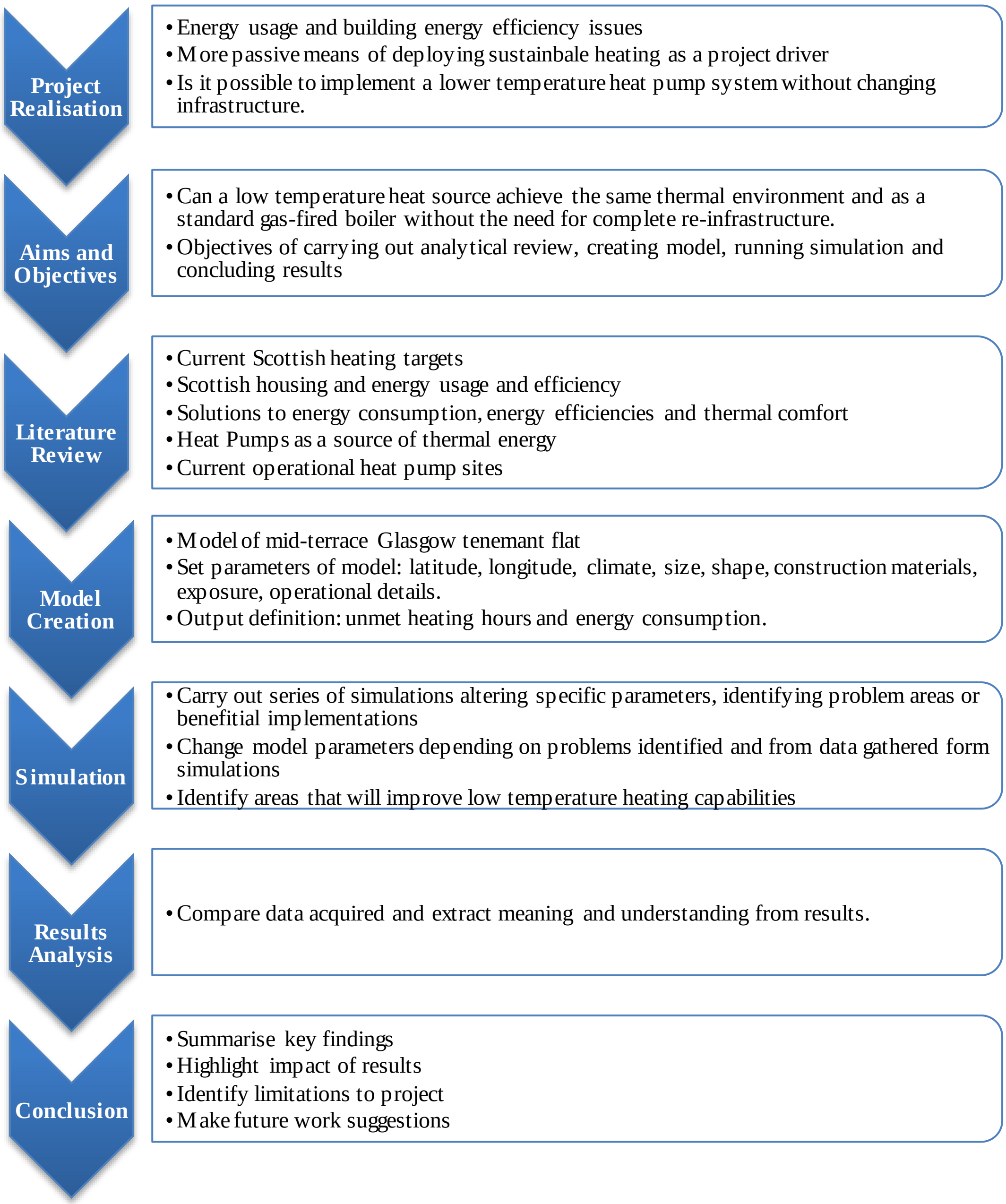

Figure 1.2. Project model identifying stages to be complete

Despite this project's focus upon tenement flats, the modelling outlined aims to address all domestic archetypes. The modelling undertaken needed to be capable of facilitating the comparison between a low temperature supplied heating system and a base case in two significant criteria; unmet heating hours and energy consumption.

The energy performance modelling software ESP-r was used to facilitate the creation of an appropriate and accurate model of a building archetype. The software allows for the analysis of energy performance through simulation to be carried out under different heating conditions. The model includes aspects such as building characteristics, location, climate, dimensions and geometries, building fabrics and materials as well as operational data, including heating, hot water and electrical demand.

A large part of accurately modelling energy performance is energy ratings including standard assessment procedures (SAP), energy efficiency ratings (EER) and energy performance certificates (EPC). The EPC gives a more comprehensive analysis of the archetype properties as well as performances on both the energy efficiency scale as well as the environmental impact scale. They also highlight to the main construction details that influence energy efficiency. Therefore, EPC, SAP and EER ratings have been used to increase model accuracy.

The model created aims to mimic the real-life structure. It needs to emulate, very accurately, the energy performance of the chosen archetype. Therefore, it is crucial that the model construction materials and fabrics match the building materials and fabrics. The more detailed and in-depth the energy model is, the more accurate the data produced will be (Barnham, et al., 2008).

After creation of the model, a series of dynamic computational simulations were undertaken to address the aims of the study. The simulation period was determined as the entire year of 2015.

The simulations focussed on implementing three identified heat pump conditions; low temperature, medium temperature and base case. The base case system was run initially to establish the standard of comparison for all other simulations undertaken. From that position, different iterations of the low and medium temperature systems were then made through changing operational details, avoiding improvements that involved invasive changes.

Once results had been retrieved, the criteria of unmet heating hours and energy consumption were used as ‘intermediaries’ for indoor thermal comfort and overall cost.

A more comprehensive review of thermal comfort can be found in "Appendix I – Thermal Comfort".

The results were evaluated and conclusions relating to each iteration were made. A synopsis and final conclusion, addressing the feasibility of integrating low temperature heat pump systems whilst avoiding re-infrastructure completed the study.

Chapter 2. Literature Review

2.1. Scottish Heating Targets

Sustainability, urban development and reduction in emissions have been identified as key issues at the forefront of present day political and governmental agendas. For Scotland, heat is the biggest influence, at 55%, on the energy sector. Heat also makes up the 47% of emissions. We spend an average of £2.6 billion every year on heating residential and non-residential buildings. However, Scotland's renewable heat sector is progressing and expected to be a market worth £2.7 billion by 2020. The Scottish Government is not only committed to supplying sustainable and renewable heat at a low cost to consumers, but is also largely focused on decarbonisation of its energy sector by 2050 (Scottish Government, 2015).

These are not the first steps that the Scottish Government has taken towards reduced heat demand. Since 2007, £45 million has been invested in the continued support of residential and non-residential construction alike. Most of the money going on methods of improving energy efficiency, renewable measures and the development of district heating schemes. Since 2009, over half a billion pounds have been allocated across a wealth of retrofit and energy efficiency programmes. Such programmes are already helping many households around Scotland to receive energy efficiency support. These measures applied by the Scottish Government are impacting upon the health and wellbeing of inhabitants giving the focus of this study an even deeper meaningfulness. (Clarke, et al., 2005).

Figure 2.1 summarises the Scottish Government's recently proposed Heat Policy Statement. It sets out how low carbon heat can be supplied to more households, residences, businesses and communities, while establishing a framework for long term investment for heat in Scotland (Scottish Government, 2015). The Heat Policy Statement highlights plans to tackle the three key aspects of heat systems:

- How the heat is used (demand and reduction)
- Distribution and storage (heat networks and heat storage)
- The heat source (heat generation options).

These three individual aspects of the policy are addressed by the "Heat Hierarchy". Although not impacting all three aspects of the hierarchy, the focus of this study has the potential to impact both the efficiency of supply and cost to consumer through supplying heat of a renewable and sustainable source; ground source heat pump.

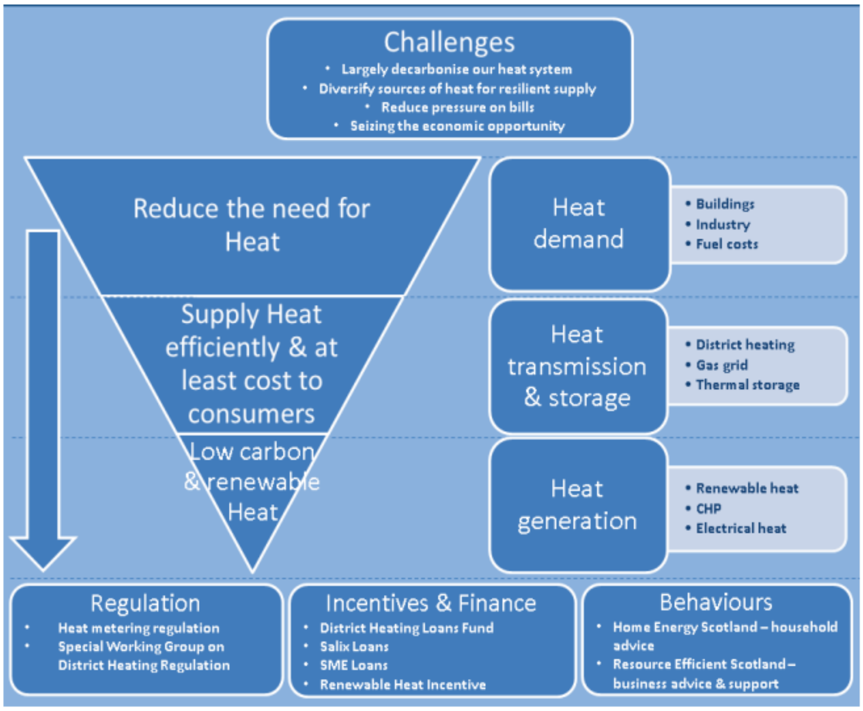

Figure 2.1. Scottish heat system and heat hierarchy (Scottish Government, 2015)

Gas makes up 78% of all primary heating systems in Scotland, electricity is 13% and oil is 6%. To meet Scotland's target of decarbonising the heating sector by 2050 all aspects of the heat hierarchy must be implemented with full efficacy. As a stepping stone towards this target, the Scottish government have set themselves a challenge of meeting 11% of non-electrical heat through renewable means. The progression of which can be seen in Table 2.1, where the most recent evaluation put 5.4% of non-electrical heat demand being met through renewable means.

Table 2.1. Renewable heat as % of heat demand (Scottish Government, 2015)

	2009	2010	2011	2012	2013	2014	2015
Total Renewable Heat Output (GWh)	845	1696	2263	2481	2904	3031	4165
Non-Electrical Heat Demand (GWh) Annual Estimate	85039	87123	85328	82722	ND	79763	77129
% Renewable Heat Output	1.0%	1.9%	2.7%	3.0%	ND	3.8%	5.4%

At the current rate of growth, it seems likely that Scotland can achieve its target by 2020. However, there is considerable room for improvement in all aspects of heating. One such aspect being the integration of low temperature heat supplied systems into hard to retrofit dwellings.

One of the largest issues is not the supply side, it is demand. A lot of heat generated in Scotland goes to waste; as a by-product of thermal and kinetic processes; leakage from poorly insulated housing; for heating unoccupied spaces; or it is used to achieve temperatures far in excess of “thermal comfort”. With lower temperature heating supplies, leakage would be minimised, the heating of unoccupied spaces would not be facilitated and temperature excess would be difficult to achieve with a thermally limited supply.

Although the targets the Scottish Government are setting are progressive, their application is not. Many renewable heating schemes being proposed apply to new builds, that are being constructed to high EPC standards, and buildings fit for energy refurbishments. When it comes to providing solutions for all dwelling archetypes, swapping to low temperature heat supplies is often accompanied by retrofit, refurbishment and re-infrastructure. This study looks at how energy improvements can be made whilst avoiding substantial ‘re-infrastructure’. The method looks at whether, the low temperature heating system can be implemented pre-retrofit, or if it can only come after intrusive retrofit measures.

2.2. Housing in Scotland

In 2015, 2.75 million dwellings were documented in Scotland (Mueller & Palombi, 2016). Table 2.2 identifies six broad categories of dwelling type characterised by their age and style.

Table 2.2. Housing stock in Scotland 2015 (Mueller & Palombi, 2016)

Housing Style	Age	Number
Old Detached Housing	pre- 1919	103,000
Old Tenement Flats	pre- 1919	218,000
Modern Detached Housing	post- 1982	228,000
Modern Tenement Flats	post- 1982	138,000
Post-war Terraced Housing	1945-1982	340,000
Semi-Detached Housing	Common through all age bands	550,000

Of these six categories tenements make up the largest individual category of all the subcategories, apart from semi-detached housing. Tenements are also the most common pre-1919 dwelling type, which can be viewed in Figure 2.2. The overall number and age of these dwellings coupled with the knowledge that tenements are hard to retrofit, makes this archetype a strong candidate for improvement through non-intrusive means.

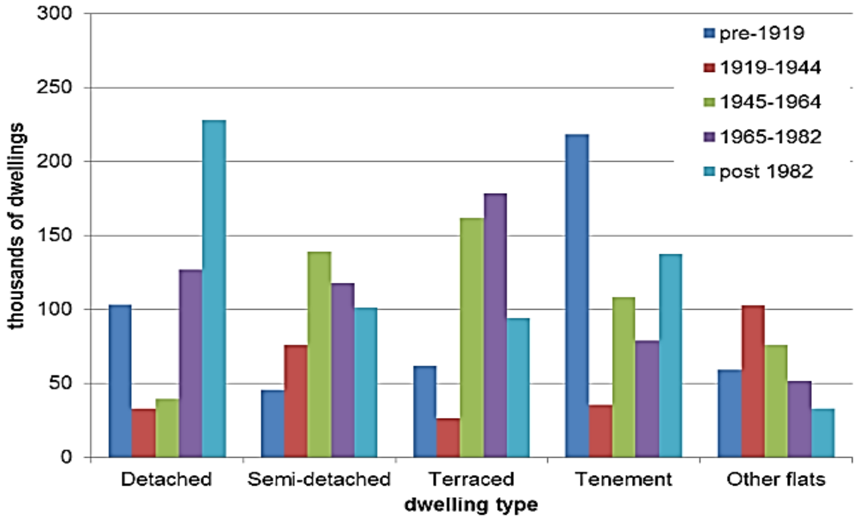

Figure 2.2. Occupied Scottish dwellings by age and type (Mueller & Palombi, 2016)

As well as being the most common pre-1919 building type, tenement flats are the most occupied (Table 2.3), and 98% of these dwellings are situated in the urban environment. Considering global urbanisation, energy efficiency within cities is crucial. The common, old and urban nature of tenements make them highly susceptible to housing upgrade programmes, retrofit efforts and increased energy efficiency work.

Table 2.3. Percentage occupied dwelling by age band and style (Mueller & Palombi, 2016)

Age of Dwelling	Type of Dwelling					
	Detached	Semi-detached	Terraced	Tenement	Other flats	Total
Pre-1919	4%	2%	3%	9%	2%	20%
1919 - 1944	1%	3%	1%	1%	4%	11%
1945 - 1964	2%	6%	7%	4%	3%	22%
1965 - 1982	5%	5%	7%	3%	2%	23%
Post- 1982	9%	4%	4%	6%	1%	24%
Total	22%	20%	21%	24%	13%	100%
Sample Size						2754000

Why Target Tenement Housing?

Around half of Scotland's housing stock is old and energy inefficient (Mueller & Palombi, 2016). Instead of building more houses with good energy performance and neglecting those properties that need attention and improvement the most, the Scottish Government needs to address older buildings, their methods of achieving and conserving heat, and reducing the associated emissions.

Glasgow specifically has targets to raise the quality of housing across all tenures to satisfactory standards, maximise energy efficiency and maintain affordable costs throughout. To achieve this, both new and old housing must be made energy efficient, contributing not only to the continued mitigation of carbon emissions, but also addressing issues of sustainability within the heat sector.

45% of Pre-1919 builds have been identified as below tolerable standard (BTS) in regular housing condition surveys. The most common reasons for this are; unsatisfactory insulation; unsatisfactory provision for lighting, ventilation or heating; and not free of rising / penetrating damp.

Figure 2.2 shows that the most commonly occupied pre-1919 dwelling type is the tenement, and Table 2.3 shows that they make up 24% of the total occupied residences in Scotland. In Glasgow alone, 52% of pre-1945 properties are tenements and of those dwellings, 7650 have been recognised as BTS. 30.6% of these buildings happen to be subject to conservation because of their unique and recognisable architectural design. Yet, most staggeringly, 96% of tenements in the East of Glasgow fail the Scottish Housing Quality (SHQ) standard (Smith, 2007).

The evidence set out above is why tenements have been the principal focus for this study. The most crucial detail to highlight about the chosen archetype of this study is the fact that they are one of the most difficult building types to improve or retrofit (Grant, et al., 2015). Their distinctive image and design makes them impossible to have exterior retrofit applied. The cavity wall that is responsible for the draughts serves a purpose in mitigating damp, rendering it untreatable. The heating systems are old and to alter them would involve heavily intrusive means. Being able to address issues of improved energy efficiency without resorting to retrofit and refurbishment measures is therefore going to be of paramount importance to this style of building.

Energy Efficiency and Performance Ratings of Dwellings

The energy efficiency of a building depends on its physical attributes: Age, type, heating systems, materials, insulation. These characteristics are documented, dwellings compared to one another and an energy assessment is produced. The assessment can be carried out through many different means, but ultimately the ratings are influenced by many different factors. The indicators of energy performance and efficiency are Fabric Energy Efficiency (FEE), energy consumption per unit floor area, energy cost rating (SAP rating), Environmental Impact rating based on CO_2 emissions (the EI rating) and Dwelling CO_2 Emission Rate (DER) (BRE, 2014).

Energy Performance Certificates (EPC) were introduced in 2009 under the EU Energy Performance Building directive. They provide a detailed account of building attributes, energy efficiency and environmental impact. These certificates use a Standard Assessment Procedure (SAP), which encompasses the energy costs, ventilation, lighting and renewable technologies, to establish an Energy Efficiency Ratings (EER) from G to A (Mueller & Palombi, 2016).

In 2015, 42% of the housing stock in Scotland had an EPC rating of C or above. However, the average rating on the EER rating is still D (Figure 2.3). Table 2.4 shows the yearly distribution of EPC ratings for housing across Scotland. Despite the continued improvement, there is still room to develop. A key feature to target therefore would be the lower rated, harder to improve dwelling types.

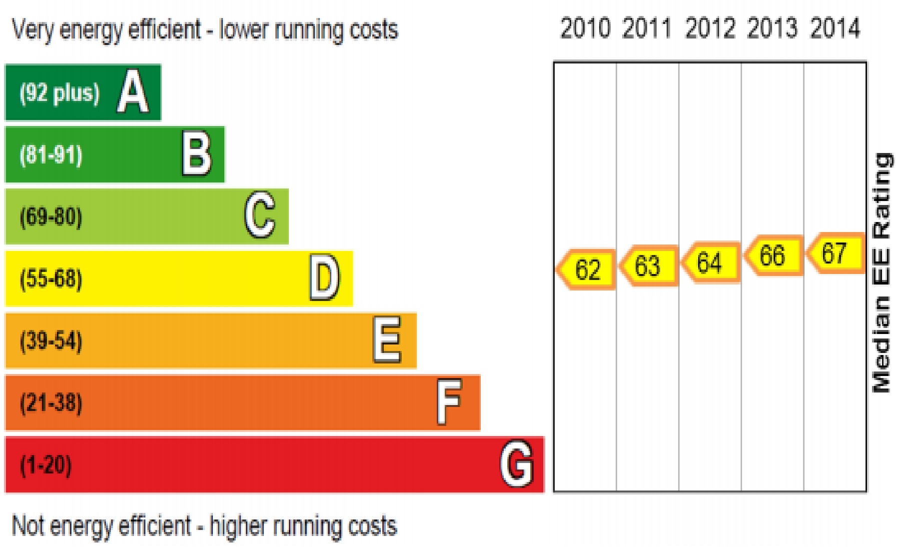

Figure 2.3. Average EER relative to EPC bands (Mueller & Palombi, 2016)

Table 2.4. Distribution of Scottish housing stock across EPC bands (Mueller & Palombi, 2016)

EPC	**2015**		**2014**		**2013**		**2012**		**2011**		**2010**	
Rating	000s	%	000s	%	000s	%	000s	%	000s	%	000s	%
A (92-100)	-	-	-	-	-	-	-	-	-	-	-	-
B (81-91)	63	3%	42	2%	29	1%	20	1%	25	1%	18	1%
C (69-80)	953	39%	939	39%	851	36%	699	29%	606	26%	547	23%
D (55-68)	1055	43%	1037	43%	1072	45%	1184	50%	1191	50%	1157	49%
E (39-54)	298	12%	321	13%	359	15%	381	16%	431	18%	495	21%
F (21-38)	59	2%	68	3%	84	4%	82	3%	96	4%	127	5%
G (1-20)	7	0%	14	0%	8	0%	21	1%	19	1%	13	1%
Total	2434	100	2420	100	2402	100	2386	100	2368	100	2357	100
Sample		2754		2682		2725		2787		3219	3115	

Looking at the EPC rating distribution in Figure 2.4, it is good to see that the ratings are slowly shifting closer to A, B or C rated builds. Yet, more than half of Scotland's dwellings (57%) monitored in 2015 retain a rating of D or worse. And so, the deployment of EER and EPCs would work as a guide for improvement through retrofit means.

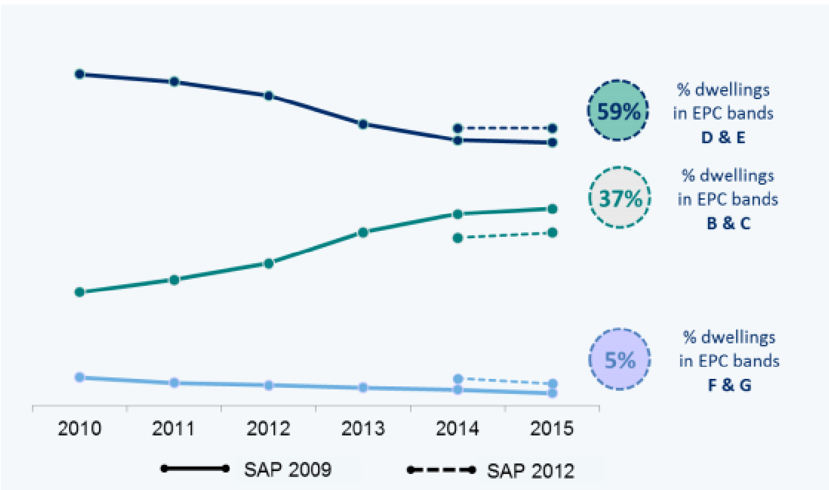

Figure 2.4. Development of EPC ratings in Scotland since 2010 (Mueller & Palombi, 2016)

Environmental Impact Rating (EIR)

Aside from the EER of a dwelling, the environmental impact ratings are evaluated to gauge the carbon emissions associated with heating, hot water, lighting and ventilation. Ratings are dependent on floor area and are therefore independent of dwelling size or type. The approach used for SAP ratings is the same methodology applied to EIR. Yet, the environmental impact and emissions associated with dwellings are not a factor covered within this study. A focus for future work however, could be the inclusion of a third criterion that is the associated emissions. Figure 2.5 shows the average EI ratings for Scotland's housing stock.

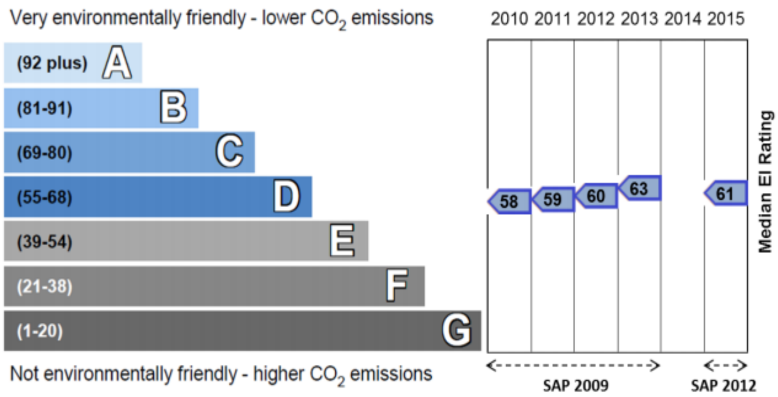

Figure 2.5. Average EIR of Scottish housing, through SAP 2009 and SAP 2012 (Mueller & Palombi, 2016)

The Low Carbon Infrastructure Transition Programme provides tailored project development support for established projects in Scotland. The programme, which was initiated in early 2015, sets out a budget of £76 million to go towards the decarbonisation and improvement of heating for private, public and community sectors (Clark, 2015). Therefore, if money is available and targeting upgrade, then the retrofit of old and hard to improve dwellings should be of high priority.

Addressing the energy supply instead of the housing conditions, the Scottish Government's Heat Policy Statement finally recognised the need for district heating, biomass, geothermal energy, solar thermal and heat pump systems (Clark, 2015). Significant efforts are being made by industry and government to incorporate renewable and sustainable heat, as well as electricity.

As part of this drive, the improvement and development of domestic heating is one of the most important. Yet this improvement does not seek solely to target energy efficiency and technological advancement. As the major contributor to emissions in Scotland, the drive to improve heating is largely focused on decarbonisation, and the impacts emissions have on health and wellbeing within cities. Determining how to tackle decarbonisation and energy efficiency within domestic heating remains a difficult and complex task.

2.3. Methods of Retrofit

Roughly 40% of the UK's energy is expended on the building sector. To decrease the associated CO_2 emissions the most cost-effective route is to reduce the energy demand (Stevenson, 2013). The installation of renewables into or onto all homes in Scotland is questionable, especially without any form of solar or wind rights protection identified within the UK planning regulations. Outside of directly integrating renewables Boardman suggests that the least cost consuming approach to achieving zero carbon is through refurbishment to an 'extreme degree' (Boardman, 2012). This however, highlights a potential flaw in the European Unions' policy framework, as they tend to emphasise "low-carbon" and not "zero-carbon" emissions at building level, yet still focus on zero-carbon at a broader scale. Alongside, Passivhaus has shifted from being a voluntary to a compulsory planning requirement for all new buildings in a lot of countries across Europe. Though the jury is still out about whether 'retrofit solutions' or 'new build' results are the most significant sustainability benefits.

An 80% CO_2 emissions reduction in buildings can be achieved without needing to resort to personal or household renewable technology installations. This can be achieved through a combination of sensible energy demand reduction measures as well as an appropriate systematic energy supply mechanism. The UK's Technology Strategy Board are focussing on the easiest gains to target their £6.5 million AIMC4 Research Programme, which addresses housing energy efficiency with a 'fabric first' attitude, without the unnecessary "eco-bling" (Stevenson, 2013).

Up until now several fabric-based solutions to improving energy efficiency and rectifying the BTS building issue have been well documented. The most obvious of these solutions being technical or thermo-physical improvements.

One such improvement was trialled in six, pre-1900 tenement builds on Sword Street, Glasgow. The cavity walls of the flat were retrofitted with several different materials, placed between the stone and plasterboard. The results were given in U-value of the wall, and were compared to the insulation quality before the retrofits. The U-Value of a material is its heat loss coefficient, and it measures how effective a material is as an insulator; lower U-values make for better insulators (The Greenage, 2013). Compared to the U-values of a new build (0.25 W/m^{2}K) the results for retrofits presented in Table 2.5 all manage to attain a similar standard.

Table 2.5. Trialled insulation types in tenement houses (Smith, 2007)

Insulation Type	**Original U-Value (W/m^{2}K)**	**Improved U-Value (W/m^{2}K)**
100 mm Hemp board	1.1	0.21
90 mm Wood fibre fitted between timber	1.1	0.19
30 mm Insulated board	1.1	0.36
50 mm Cellulose fibre	1.1	0.28
40 mm Insulated board	1.1	0.22
50 mm Bonded Polystyrene bead	1.1	0.31

Another focal point of improvements to older buildings is the windows. Originally single glazed, a large proportion of buildings, especially flats, have upgraded to double glazing. Although increasing the U-value of the window by a significant margin, the improvements that can still be made to the windowed area are considerable. This kind of enhancement is mostly associated with the technological and thermo-physical aspects of improvement.

More experimental retrofit techniques have been investigated within the University of Strathclyde, that looked at providing passive solutions involving the use of glass to address insulation in regions of cold climate (Anagnostou, 2016). The technical term for these approaches is “greenhouse residences”. The approach has the potential to reduce energy demand by as much as 25%. Despite the obvious benefits of such retrofit, the technology is still at research level.

A less thermo-physical and less intrusive improvement, would be the integration of a renewable or sustainable heat source. Over recent years there have been a small portion of tenements turning to electricity as a secondary source of heat. However, the substantial majority of properties use single unit gas-fired boilers as a primary heat source. A solution to this is to turn to renewable and sustainable sources like heat pump connected district heating. The single unit boiler would be removed, replaced with a heat exchanger, supplied by the district heating scheme, and this could continue to supply the wet heating system.

2.4. Heat Sources

Heating systems are a crucial factor in the thermal efficiency, and therefore energy efficiency of a dwelling. Gas is the most popular source of heat in all dwelling types across Scotland, at around 85%. In fact, roughly 16% of houses in Scotland sit outside the gas grid. 93% of urban dwellings are covered by gas and as a result it is the most inexpensive major commercial fuel explaining its popularity.

Gas-fired boiler efficiencies are dictated by the energy efficiency and building standards alike. Since 1998, boiler efficiency standards were established by the European Council. However, in 2007 the Scottish Building Standards increased the efficiency requirements for new or replacement boilers, which could be deemed a responsible step towards energy efficiency and decarbonisation. Gas grid accessibility has a strong impact on cost of heating and therefore the EER of homes.

The most common urban residence type is the tenement flat, which makes up around 30% of urban housing (Mueller & Palombi, 2016). The largest proportion of houses using gas as their primary fuel source also happen to have been built between 1919 and

1982. If heating issues can be addressed in the largest urban dwelling type, then a significant impact can be made on the decarbonisation and overall energy performance of the Scottish housing stock.

Decentralised Heat Source

There are approaches that can be employed to facilitate the improvement of heating in buildings. Examples like the electrification of heat, or converting to using gas from oil and switching to CHP are good examples that have already been implemented. Another viable option would be the use of decentralised energy (TÜV SÜD Wallace Whittle, 2016).

Decentralised energy refers to the generation of energy outside of the main grid, for example, micro-renewables schemes (heating included). This energy can come from waste plants, combined heat and power (CHP), geothermal sources, biomass or solar irradiation, and then be distributed through district heat networks. Such schemes can span single buildings or entire cities (Tipper, 2013). Decentralised energy is an effective and efficient way to meet demand, at the same time as improving energy security and sustainability. To exemplify the benefits of district heating, Table 2.6 highlights how larger district heating schemes offer significantly reduced demand requirement. This would be particularly interesting to model at a tenement block (as opposed to close) scale.

Table 2.6. Reduced heating capacity requirement for district heating (TÜV SÜD Wallace Whittle, 2016)

Option	**Dwelling**	**Space Heating Div**	**Domestic Hot Water Div**	**Occupancy**	**Un-diversified Demand**	**Diversified Demand**
Combi Boiler	1	100%	100%	100%	33 kW	33 kW
Communal Boiler	50	100%	11.2%	100%	1,650 kW	264 kW
Central Boiler	3,000	100%	4.1%	100%	99,000 kW	9,119 kW

District Heating

Decentralised heating systems can be harder to facilitate than conventional systems. The capacity to distribute heat is paramount compared to the actual heat generation. District heating utilises large networks of very well insulated pipes ("Appendix II – District Heating Piping") to transport heat, usually in the form of hot water or steam, across large distances; these being called heat networks. These heat networks are controlled using variable speed pumps, monitoring systems and optimised route, temperatures, diameters and insulation thicknesses. Although not completely self-sufficient as the pumps require electricity, the pipe sizing can drastically impact upon operational costs.

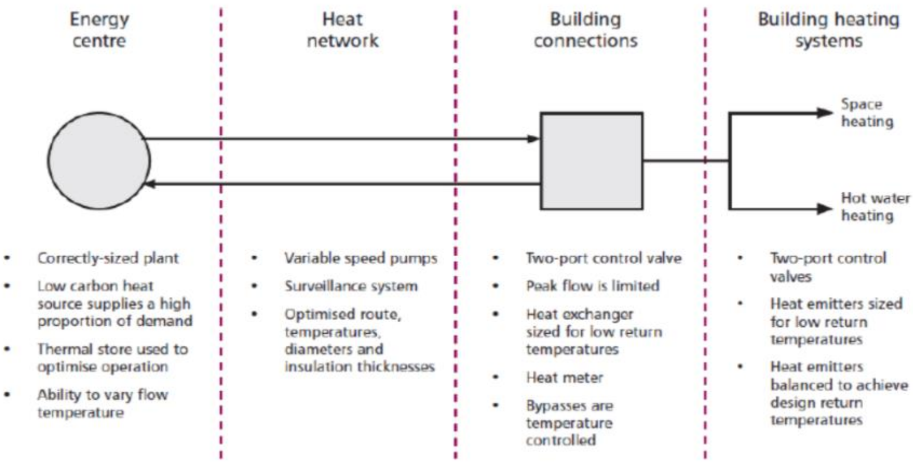

Figure 2.6. Overview of district heating system and operation (TÜV SÜD Wallace Whittle, 2016)

Heat networks are efficient and effective replacements for major heat supply in built up and urbanised areas (Carvalho, et al., 2016). The primary advantage being the potential to integrate alternative heat sources that might otherwise not be exploited due to their low feasibility in small scale situations. The use of well-developed heat networks to distribute heat from sources like geothermal, waste energy and heat pumps contributes to improved efficiency of urban energy consumption and a reduction in carbon emissions.

Several good examples of where heat networks have been integrated to great effect can be seen across the world. Areas with geo-thermal heat (e.g. Reykjavik) have long used such methods – so there is an element of reapplying well established old methodologies. For example, in Aberdeen the City Council made the decision to connect areas of social housing to a district heating scheme (Tipper, 2013). The project includes over 1500 flats as well as 8 public use buildings. Cost of heating per residence has taken a staggering fall by 50% and carbon emissions have also reduced by 45%.

In London, the Bunhill CHP network provides heat and power to 850 homes as well as two leisure centres. The scheme saves 1800 tonnes CO_2/ year, which accounts for a 60% reduction in CO_2 emissions for the whole project (Islington Council, 2013). The Bunhill heat network is powered by a 1.9 MWe gas CHP turbine, and provides 2 km of insulated district heating pipes with heat (“Appendix III – Islington and Bunhill Heat Network Scheme).

At a greater scale the brand new geothermal district heating plant in Villejuif, within the greater area of Paris, has a predicted production of 220 GWh/ year, making it the largest geothermal district heating system in Europe (Richter, 2017). The Chevilly-L’Hay-Villejuif geothermal heat plant is a typical example of renewable and economical energy.

The heat itself is provided by an aquifer deposit that reaches depths of roughly 2 km, and holds water at temperatures between 56˚C and 85°C. The heat is exploited through two wells, one to pump the water up and another to return the water to the reservoir. For the heat network to provide heat, the plant must facilitate a successful heat exchange between the reservoir water and the freshwater within the heat network. The heat exchanger used consists of 350, 1mm thick titanium plates that facilitate the heat transfer so it can be provided to residences alike.

The Chevilly-L’Hay-Villejuif heat network provides renewable, sustainable and economical heating to 30,000 dwellings. Residential and non-residential buildings such as schools, hospitals, swimming pools and industrial offices are served. If production from the plant is successful, an overall increase in power production to 300 GWh/ year could be expected (Figure 2.7).

2.5.Heat Pumps

Heat can only be transferred from areas of high temperature to areas of low temperature. If work is done on a thermodynamic cycle, the cycle can work in reverse, transferring heat from areas of low temperature to high temperature (Bundschuh & Chen, 2014).

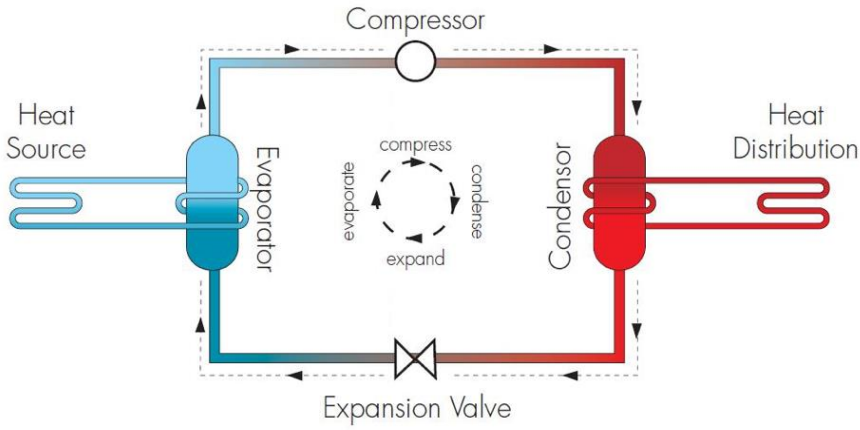

Figure 2.7. Basic heat pump cycle (European Comission, 2016)

Heat pumps operate in similar ways to refrigerators and air conditioning units. When the working material converts from a liquid to a gas it absorbs heat. When the same material reverts back to a liquid from a gas by condensation, it releases heat. The phase change conditions are dictated by the temperature-pressure relationship. Heat pumps use this relationship to facilitate the transfer of heat from a heat source to a heat sink.

Heat pumps are capable of extracting heat from a low-temperature heat sources, like geothermal energy, through the evaporator component of the cycle and raising the extracted heat to a high-temperature at the condenser unit of the cycle (Kuzgunkaya & Hepbasli, 2007).

This kind of heat pump is called a Ground Source Heat Pump (GSHP). Compared to deep geothermal, GSHP operate at depths of roughly 9 metres, where temperatures are relatively constant compared to air or water. The coefficient of performance (COP) of a heat pump is the ratio of power needed to the drive the compressor, to the heat delivered to the sink. The COP is used to calculate the efficiency of an ideal heat pump.

$$COP = \frac{Q_L}{W} = \frac{Q_L}{Q_H - Q_L} = \frac{T_H}{T_H - T_L}$$

Where:

Q	=	Heat
W	=	Work done on the heat pump
T	=	Temperature (K)
H	=	Denotes "High Temperature"
L	=	Denotes "Low Temperature"

The COP of a heat pump decreases as the temperature of the heat sink and heat source become further apart. As well as the obvious heat loss within the cycle there is frictional losses throughout. The compressor and evaporator require a substantial temperature difference to enable successful heat exchange and the actual COP of a heat pump is lower than that of an ideal heat pump. However, to establish an economic advantage is it important that the COP be greater than 3.

Heat pumps have been chosen as the heat source within this study due to the lack of deep geothermal sources, and instead the availability of large shallow mine workings within and around Glasgow (Gillespie, et al., 2013) (Harber, 2013). Also, considering the mild and non-extreme climate conditions of the location, the efficiencies of the heat pumps can be optimised to raise the COP and therefore reduce costs relating to operation.

Heat Pumps in District Heating

The incorporation of heat pumps into heat networks has significant potential to decarbonise the electricity grid, as well as offering improved methods for deploying sustainable heat. CO_2 savings of 48% and upwards are achievable, depending on the scenario in which the heat pump is used (Foster, et al., 2016). The incidental CO_2 savings happened to be greater where:

- Heat pumps provide a larger heat demand
- The lower the source-sink temperature difference, the greater the operating efficiency
- Thermal losses in networks are lower in lower temperature systems.

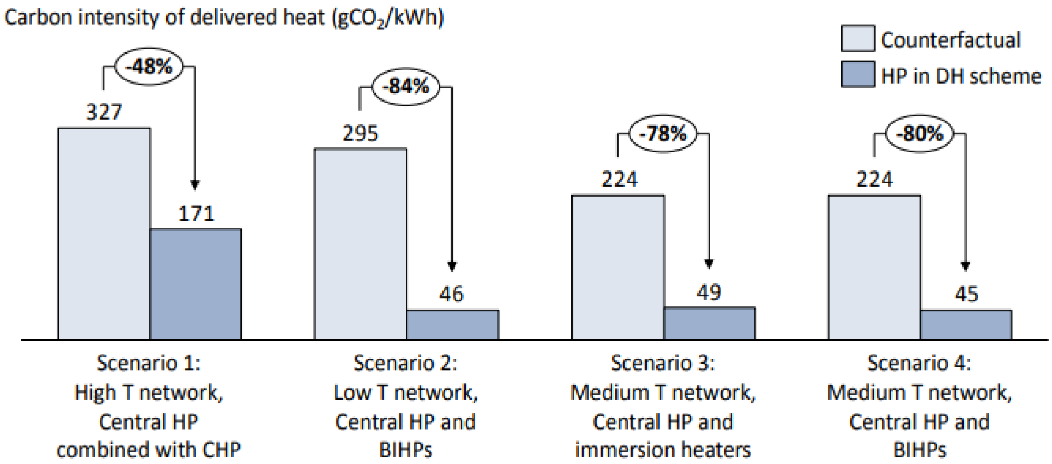

Figure 2.8. Carbon saving of heat pump network compared to CHP and gas-fired boilers (Foster, et al., 2016)

Despite the decarbonisation benefits, the cost of heating provided by heat pump incorporated district heating schemes is likely to be higher than the gas-fired boiler based district heating scheme. With an increase in price by as much as 70% this can largely be attributed to:

- High capital cost of heat pump implementation
- Electricity price is higher than the price of gas
- Low revenue from heat pump schemes compared to gas
- Greater heat requirement of the heating plant
- Greater network implementation costs

It is important however to note that heat pumps have the potential benefit of being able to shift the economic unbalance in their favour. This is particularly evident if cooling, as well as heating was requirement of the heat pump.

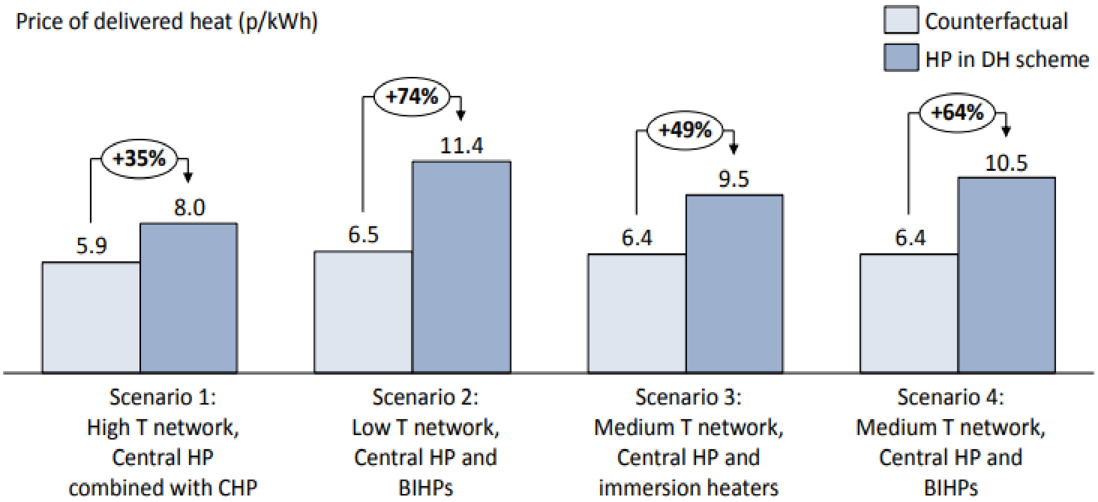

Figure 2.9. Cost incursion of swapping from gas to heat pump provided heat (Foster, et al., 2016)

It is therefore important to have a scheme designed around carbon emissions and running cost.The four scenarios carried out in the study carried out by Foster *et al.* (2016) show that the cost incurred relating to the CO_2 savings achieved by implementing heat pumps was between £133-277 / tCO_2. Therefore, this analysis suggests that if large CO_2 savings are to be made, the UK government's financial support in the form of renewable heat incentives (RHI), must be preserved.

District heating can therefore be seen as a balancing act. It is important to balance up all factors that affect the implementation of such schemes. One factor mentioned but not expanded upon is the cost of implementation, which likely includes the need for complete retrofit of new heating systems within buildings.

This study aims to answer the question of whether there is a need for re-infrastructure or is there a lesser alternative. Not referring to the large-scale implementation of the entire scheme, but just the integration within residences such as tenement flats. Is a small scale, low key application of district heating at tenement scale advantageous because it is simple to install? Results have been shown that help clarify the potential of heat pumps and district heating as suitable re-use scenarios for older housing stock.

2.6. Heat Pump Powered District Heating Case-Studies

Several existing heap pump supplied district heating schemes have been highlighted below. As well as offering insight into the performance abilities of such systems, they have been used to provide crucial information and details to the modelling process within this study. More specifically, the heat delivered in both the Helsinki and Wandsworth schemes have been used to represent supply temperatures within the modelling and simulation section.

Helsinki

Helsinki has a large district heating and cooling network. The scheme provides 90% of the city's heat demand, as well as a large portion of the cooling demand. The heat network is provided by gas-fired CHP and the cooling by absorption chillers. 84MW of heat pump capacity were incorporated into the arrangement in 2006, with the intention of implementing heat storage as well as increased heat pump capacity (Foster, et al., 2016).

The heat network is provided by five 16.8 MW heat pumps. The operation of the heat pumps depends on seasonal heat shifts, and where heat can be sourced. During colder months, temperatures of 50-62˚C can be recovered from sewage, and cooling is provided directly from by sea water. In the warmer months, the heat pumps operate to meet cooling loads, where heat extracted from the cooling network is used to heat the heating network to temperatures of 88˚C (Foster, et al., 2016). The operations cycles and operational parameters can be viewed in "Appendix IV – Helsinki Heat Pump District Heating Scheme Operations ".

Wandsworth Riverside

A development situated on the banks of the Thames that is projected to supply 504 apartments as well as substantial commercial and leisure space when the project has been fully developed. An aquifer thermal energy storage (ATES) system was developed to provide space heating and cooling. Hot water and heat pump back up are provided by gas boilers and a gas CHP.

The system operates through three heat pumps connected to an aquifer beneath the site via an open-loop system of eight 120m deep boreholes. The heat pump cooling supply has a capacity of 2.25 MW and a heating output of 1.2 MW. During warmer months, the aquifer heats up because of rejected heat from the cooling loads, which in turn provides a better heat pump performance through winter. In contrast, during the colder months the aquifer is cooled as heat is drawn out for space heating, which cools the aquifer leading to higher COP for summer operation. Under ideal conditions, the aquifer is cool enough to directly cool the cooling circuit, and the heat supplied for space heating and water heating are distributed using separate networks (Foster, et al., 2016). The schemes and operation parameters for the Wandsworth riverside scheme can be seen in “Appendix V – Wandsworth Riverside District Heating Operation ”.

Duindorp

The heat pump and heat network system installed in Duindorp, Netherlands was installed during the construction of 789 apartments. The system was designed to reduce energy costs as well as lower environmental impacts when the older housing stock on site was replaced with the new. The scheme operates using a water source heat pump (WSHP). The network is a low temperature network which is maintained between 11˚C and 18˚C. Each apartment has a water-to-water heat pump installed to make full advantage of the low temperature source. These individual heat pumps use the low temperature network as their heat source, raising the temperatures to 45˚C for space heating and 55-65˚C for hot water. Just as with the previous two case studies the operation of the system varies seasonally. During winter the main heat pump raises the sea water from 6˚C to 11˚C. This is the temperature the water is distributed at and the single unit heat pumps raise the temperature even further for space and hot water heating. In summer the seawater exceeds 11˚C and therefore the central heat pump is not needed, the individual heat pumps operate the same way.

There are many advantages included in Duindorp scheme. The low network temperature ensures very low network heat losses, but the temperature is significant enough to avoid the need for antifreeze being incorporated into the network. The heat network can be used for cooling during the summer. However, the installation capital cost involved an additional €5,500 per dwelling compared to conventional gas-fired boiler system (Foster, et al., 2016). The simple schematic of the Duindorp heat network, as well as the technical parameters can be viewed in "Appendix VI – Duindorp Water Source Heat Network .

Brooke Street, South Derbyshire

An off-gas grid district heating development which supplies 18 local authority owned flats. An arrangement of GSHP are used to supply the heat network for the local builds. At the same time as the installation of the scheme, fabric retrofits were deployed to help improve thermal efficiency of the dwellings. The details of the scheme can be found in "Appendix VII – Brook Street GSHP Network Technical Parameters ".

Three GSHP coupled to a common ground loop serve three blocks of six flats through 28 boreholes, each 100m deep. Space heating and hot water are supplied to each flat.

Heat pumps were chosen over conventional heating methods for Brooke Street as it is not connected to the gas grid. Previous heating schemes had been 100% electrical, utilising storage heaters. Complaints from residents regarding high running cost and low control triggered the council to explore renewable energy solutions and funding through renewable heat premium payment, which would partly cover the cost of the heat pump scheme (Foster, et al., 2016).

Wynford Estate, Glasgow

The Wyndford Estate scheme in Glasgow, provides for 2000 homes and is set to save 7000 tonnes of CO_2 a year, which is the equivalent to 1000 new homes. The scheme utilises a 1200 kWh centralised CHP unit and a thermal store with a capacity of 120,000 litres. which alleviates a great deal of cost on both the economic and environmental scales (Parson Brinckerhoff, 2012). The scheme plan is attached in "Appendix VIII – Wyndford Estate, Glasgow CHP District Heating Scheme ".

Govanhill and Pollockshields, Glasgow

The district heating scheme study has been carried out on three areas of southside Glasgow; Govanhill (central), South West Govanhill and Pollockshields East. The initial focus of the study was to connect the 3400 homes to a district heating scheme, with heat being provided by Glasgow's Renewable and Recycling Energy Centre, which is situated nearby. It has been calculated the scheme would save 22,000 tCO_2e a year for these dwellings.

Like this project, the main drawback of the district heating scheme is the complexity of installing pipes to facilitate the system. It was proposed that, for a block of tenements identified as suitable candidates for the project, its heat pipes would be connected up the rear walls of the building. A heat exchanger and heat meter could be fitted in place of the present boiler and this sole installation would move the dwellings from an EER of G to D (South Seeds, 2016). The proposed sites, heat demand and theoretical implementation of the scheme can be seen in "Appendix IX – Govanhill and Pollockshields, Glasgow District Heating .

Chapter 3. Modelling and Simulation

To assess the feasibility of implementing a low temperature heat source, such as ground source heat pumps and heat networks, in Glasgow tenement flats, like in Govanhill, a modelling method has been devised. All parameters that must be applied to the model have been highlighted in the Method section, but are further explained with direct respect to tenement flats. As the focus of the study, thermal comfort is the key output that is monitored through the proxy 'unmet heating hours'. A more in-depth review of thermal comfort and PMV can be found in "Appendix I – Thermal Comfort". Certain parameters (detailed below), within the model have been altered to have a positive impact on unmet heating hours.

As well as thermal comfort, cost incurred through altering parameters has been represented through total energy consumption (kWh). Comparisons were conducted between the different model iterations to determine the feasibility of integrating a low temperature heat source.

Upon review of the modelling and simulation results, a calculated judgement was made as to whether GSHP and district heating could be appropriate in replacing gas-fired boilers in tenement flats (Figure 3.1).

Figure 3.1. Pre- 1919 Glasgow tenement building (Bridgestock, 2016)

For the modelling and simulation process to proceed a model of a tenement was subjected to several different circumstances that evaluate the ability of the district heating system to stand up against the gas-fired boilers. To make the model as accurate as possible, it was built and simulated on the energy performance software ESP-r.

3.1. Model Design

Before beginning simulations, parameters were researched and set within the model to exactly imitate all aspects of a tenement flat. This model design sequence follows the steps identified in the Method section that are necessary to produce an accurate energy performance model:

- **Building characteristics** (building style, age, location and orientation): The building in question is a 2 bedroom, mid-terrace, pre-1919 tenement flat located in Glasgow, Scotland. The flat has two external exposed walls. The property has an east-west orientation with the main living space facing northwest.

- **Dimensions** (floor space, height, exposed wall dimensions and overall volume): Relatively large floor space, $64m^2$, with high ceilings (compared to those of more recent builds) and typical tenement characteristics of a large window area.

- **Building fabric** (wall, roof and floor construction, insulation type, window type, U-Values): Uninsulated, "hard-to-treat" 0.6 m sandstone exterior, single glazed sash and case windows, minimal draft proofing and non-exposed floors.

- **Heating and hot water** (heating systems, hot-water systems and control): Reasonably new standard gas-fired boiler was used to represent a base case system with an ideal heating control, allowing for instant supply of max available power. DHW has not been considered as it has no impact on the scope of this study (Barnham, et al., 2008).

An EPC was acquired for the tenement building archetype that can be seen in Table 3.1. Key parameters were identified within the certificate and then replicated within the energy performance model to improve its accuracy.

Table 3.1. EPC of mid-terrace Glasgow tenement flat (Barnham, et al., 2008)

Elements	**Description**	**Current performance**	
		Energy Efficiency	Environmental Impact
Walls	Cavity wall, as built, no insulation (assumed) Cavity wall, as built, partial insulation (assumed)	Poor Average	Poor Average
Roof	(other premises above)	Good	Good
Floor	(other premises below)	-	-
Windows	Single glazed	Very poor	Very poor
Main heating	Boiler and Radiators, Gas-fired	Good	Good
Heating controls	Programmer, timer, thermostat	Average	Average
Secondary Heating	Room heaters, Gas-fired	-	-
Hot water	From main system (gas-fired)	Good	Good
Lighting	Low energy lighting in majority of fixed outlets	Good	Good
	Current energy efficiency rating	D63	
	Current Environmental impact		D57

Building Characteristics

The first parameters set were the model context, or building characteristics. This included important information like latitude and longitude (55.8642° N, 4.2518° W) that dictates the climate and solar timings to which the model was exposed. The exposure of the model was set as an urban environment, as shown in Figure 3.2. The year for simulations was set to 2015 as stated in the Method, in section 1.5.

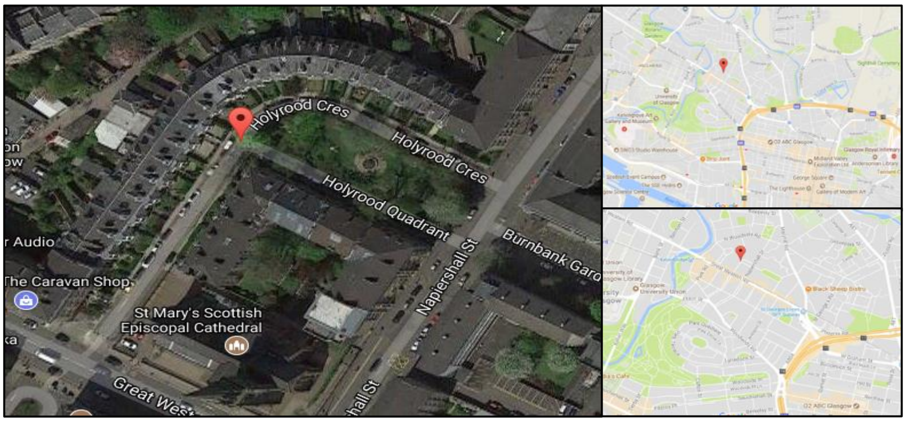

Figure 3.2. Holyrood Crescent on Map of Glasgow (Google Maps, 2017)

Dimensions

The next factors to be established within the model were the geometries, dimensions, construction materials and properties of each section. The model is a basic, but geometrically and structurally accurate, emulation of a two-bedroom tenement flat (Figure 3.3). In total six construction materials have been used, however there are thirteen surfaces that have been identified as one of these six materials.

Two different zone types have been recognised within the flat due to their differences in dimensions. These zone types can be understood as the living area (zone 1), which represents the larger rooms and the bedroom (zone2), which represents the smaller rooms.

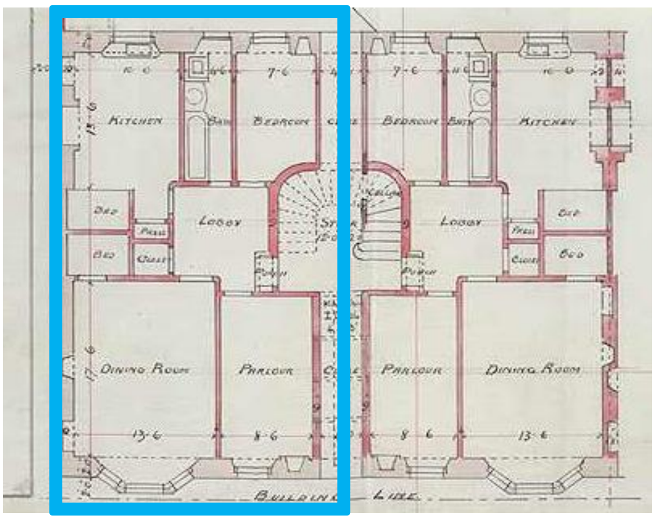

Figure 3.3. Holyrood Crescent tenement flat floor plan (The Glasgow

Building Fabric

Table 3.2 highlights building materials and fabrics used in the ESP-r model. A detailed description of each surface including thicknesses, conductivity and heat density have been given, as well as a final U-value for the surface. Most of the fabrics applied have been taken from literature or EPC ratings (Barnham, et al., 2008).

Table 3.2. Structural materials and fabrics used within model

Surface Type	***Construction details***
Internal wall	Surface|Mat|Thick |Conduc-|Density |Specif|IR |Solr| Description layer |db | (mm) |tivity | |heat |emis|abs | Wall-1 is composed of intern_wall and is opaque: 1 103 12.0 0.180 800.0 837.0 0.91 0.60 perlite plasterboard 2 2 150.0 0.440 1500.0 650.0 breeze block 3 103 12.0 0.180 800.0 837.0 0.91 0.60 perlite plasterboard ISO 6946 U values (hor/up/dn heat flow) for intern_wall is 1.552 1.628 1.461 (partn) 1.362
Cavity wall	Wall-2 is composed of cavity_brick and is opaque: 1 4 100.0 0.960 2000.0 650.0 0.90 0.93 outer leaf brick 2 0 40.0 0.000 0.0 0.0 air gap (R= 0.150) 3 3 100.0 0.620 1800.0 840.0 inner leaf brick 4 101 12.0 0.500 1300.0 1000.0 dense plaster 5 113 10.0 0.700 1400.0 920.0 0.91 0.70 lime plaster ISO 6946 U values (hor/up/dn heat flow) for cavity_brick is 1.603 1.684 1.507 (partn) 1.401
Window	F1 is composed of single_glaz & optics SCF8783_06nb 1 243 6.0 1.050 2500.0 750.0 0.83 0.05 clear float ISO 6946 U values (hor/up/dn heat flow) for single_glaz is 5.691 6.863 4.636 (partn) 3.763 Clear float 87/83, 6mm, no blind: with id of: SCF8783_06nb with 1 layers [including air gaps] and visible trn: 0.87 Direct transmission @ 0, 40, 55, 70, 80 deg 0.779 0.759 0.717 0.581 0.348 Layer| absorption @ 0, 40, 55, 70, 80 deg 1 0.149 0.163 0.173 0.179 0.169
Door	Door is composed of int_doors and is opaque: 1 69 25.0 0.190 700.0 2390.0 0.90 0.65 oak ISO 6946 U values (hor/up/dn heat flow) for int_doors is 3.316 3.682 2.928 (partn) 2.554
Ceiling + Floor	Layer|Thick |Conduc-|Density|Specif|IR |Solar|Diffu| R | Kg |Description |(mm) |tivity | |heat |emis|abs |resis|m^2K/W| m^2| 1 240.0 0.510 1400. 1000. 0.90 0.25 10. 0.47 336.0 block white ptd : block white painted inner (3% mc) ISO 6946 U values (horiz/upward/downward heat flow)= 1.561 1.638 1.469 (partition) 1.369 Weight per m^2 of this construction 336.00

Extra Operational Details

With the framework and construction of the model established some operational parameters for the model had to be set. On the ESP-r, the operations consider two factors: Scheduled air flows and casual gains. These operations are set based on data retrieved for the archetype being modelled.

Scheduled air flows represent ventilation and infiltration within the model. Pre-1945 Glasgow tenement flats were built with structural timber beams placed against the outer brickwork of the building. The buildings were created with a cavity wall to help mitigate dampness and rot from destroying these main structural beams. The side effects however of this design meant that the flats within the building were draughty.

The software has a default value for air changes per hour (AC/h) of 0.5, which is the air tightness of a Passivhaus standard building. Taking this into account, as well as the study carried out by Howieson *et al.* (2003) the scheduled air flow for the model has been parameterised and set to 1.7 AC/h. (Howieson, et al., 2003).

In tenements, infiltration is the only form of air flow taking place. Infiltration is the movement of air from outside to inside through cracks, leaks and holes in the building materials, in fact infiltration can sometimes be referred to as air leakage (ASHRAE, 2005). Due to the heightened levels of infiltration the need for ventilation has been not recognised.

Casual gains are heat changes inside a building that arise from three factors not associated with heating; occupants, lighting and small power appliances. In this study, thermal environment is the key parameter being monitored, therefore it is expected that the model is occupied at some points during the simulation period. To emulate a real tenement, two occupants have been added to the model. The presence of these occupants within the model was assumed and have been modelled in terms of the heat they emit.

A single, central light has also been deployed within the model and a control loop that dictates when the light goes on and off daily has been implemented. This control loop generally coincides with the presence of the occupants within each zone.

For the simplicity of the study, no small appliances have been implemented within the model. Figure 3.4 shows both the sensible and latent gains incurred by the model's operational details.

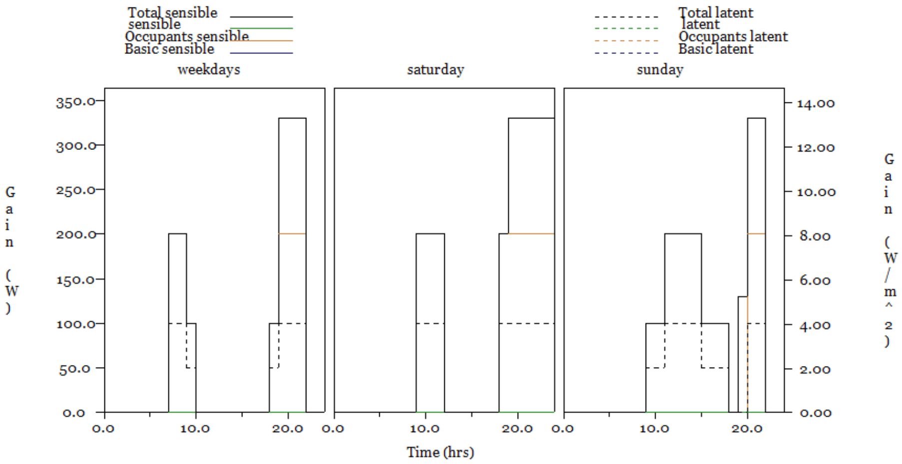

Figure 3.4 Graphical representation of internal casual gains of model

Heating and Hot Water

The final, and most important, parameter of the model to be defined was the heating system. Based on the daily schedule of the two hypothetical occupants, a control loop for three day types (weekday, Saturday and Sunday) was created for each zone type. The timings of the control loop are presented in Table 3.3. The loop specifications included a heating set point of 21˚C and a maximum heating capacity that would later be determined by the simulation type.

Table 3.3. Heating schedule of energy performance model

Zone Type	**Heating Schedule** *Morning*	*Evening*
	Weekday	
Zone 1	07:00 – 09:00	18:00 – 22:00
Zone 2	07:00 – 09:00	21:00 – 23:00
	Saturday	
Zone 1	07:00 – 13:00	18:00 – 24:00
Zone 2	07:00 – 09:00	21:00 – 24:00
	Sunday	
Zone 1	07:00 – 22:00	
Zone 2	07:00 – 22:00	

For the sake of the study an ideal heating control has been integrated, allowing the heating system to provide as much heat as possible when it is required. This in turn is dictated by the operational hours which are based on the inhabitants of the dwelling. The heating schedule has been adapted to meet the requirements of two occupants. Morning operational times coincide with the occupants waking up, evening times coincide with the occupants returning from their daily activities. Weekends operate for longer as the occupants are assumed to spend more time within the flat.

Another aspect of the heating system is domestic hot water (DHW). For the sake of this study, the DHW has not been addressed as it does not contribute to the thermal environment of the energy performance model. Space heating is the key concern within the study, and therefore all parameters relating to it have been considered.

With all the parameters to the model determined the next stage was to run the model through some simulations that would highlight how it holds up against the climate profile of Glasgow in 2015 and so test the efficacy of the heating systems to be integrated.

3.2. Simulation Approach

Using the model developed in the section above the feasibility of integrating a low temperature heat pump scheme without the need for a complete re-infrastructure of internal heating systems could be studied. A set of simulations were devised that would best show the results of altering the heating system.

Three simulation types were proposed; base case, medium temperature and low temperature. The base case operating run was established as a current gas-fired boiler heating system that could achieve maximum heating demand.

Heat pump design has a large impact on the temperature that can be supplied. The higher the input temperature, the lower the efficiency (COP) and the greater the running cost. This is the reason behind testing not only a low temperature, but also a medium temperature system. Although, it can be expected that the medium temperature system will perform better, the costs incurred will be a lot higher. On the other hand, the costs in the low temperature system are lower, but the thermal capabilities decrease.

The systematic approach used to facilitate the simulations assumed that each zone within the model was fitted with a single convective and radiative radiator. The thermal capacity of the radiator was dictated by the power input, which in turn was determined by the temperature of water supplied by the heat pump, to the heat exchanger that would theoretically replace the gas-fired boiler within the tenement flat.

Power Input

Before progressing to the simulations, a method of determining the medium and low temperature heat pump systems needed to be formulated. From review, it was determined that the base case heating system would have a ΔT of 60. ΔT60 is the normal radiator operating ΔT according to the British Rating System (The Radiator Centre, 2017). A short calculation can be carried out using temperature measurements showing how the ΔT was established:

$$\mathbf{\Delta T} = mean\ water\ temperature - air\ temperature$$

$$\mathbf{\Delta T} = \frac{(90 + 70)}{2} - 20$$

$$\mathbf{\Delta T} = 80 - 20$$

$$\Delta\mathbf{T} = \mathbf{60}$$

$$\rightarrow \Delta\mathbf{T60}$$

The temperatures used within the calculation represent the inlet temperature, 90˚C, the return temperature, 70˚C, and the ambient air temperature, 20˚C. These measurements can also be represented in the following format 90/70/20˚C (Radson, 2012).

To determine the supply temperatures of the medium and low heat pump systems, details from the case studies of Helsinki and Wandsworth were used. The inlet temperatures of 60˚C and 45˚C, respectively, along-side assumed return temperatures and a constant air temperature of 20˚C, allowed for the medium and low system ΔT to be calculated.

The medium temperature heat pump system was determined to have an inlet temperatures of 60˚C, acquired from the system used in Helsinki (Foster, et al., 2016). A return temperature of 40˚C was assumed and air temperature of 20˚C; 60/40/20˚C. Using the calculation stated above the ΔT was calculated to be ΔT30. This meant that the heating system would suffer and 50% decrease in power available to the system.

The low temperature heat pump system was established to have an inlet water temperature of 45˚C**,** again verified by the scheme in Wandsworth (Foster, et al., 2016). A return water temperature of 30˚C was assumed and an air temperature of 20˚C was retained; 45/30/20˚C**.** This meant the low temperature system was classified as ΔT15, incurring a 75% reduction in heat available.

The initial step to gaining results of the efficacy of base case against medium and low temperature systems involved determining the maximum power requirements of the heating system. An initial simulation was undertaken setting the power available as unlimited. The result of peak power consumption and date that it was achieved were determined (Table 3.4).

Table 3.4. Standard heating conditions, maximum power requirement

	Max Power Requirement (kW)	**Occurrence (date & time)**
Tenement	10.2	09 January, 07:37

After establishing the maximum power requirement for the base case system, the medium and low temperature systems power requirements could be calculated through applying the relative power reductions. The final input powers to each system can be seen in Table 3.5.

Table 3.5. All simulation type input powers

	Input Power (kW)		
	Base Case System	*Medium Temperature System*	*Low Temperature System*
Tenement Model Total	10.2	5.25	2.42

With the power requirements for the medium and low temperature systems set (Table 3.5), the values could be applied to the model's heating control loop and further simulations carried out.

Iterations Performed

As well as altering the power input of the heating system and therefore mimicking the integration of low and medium temperature heat pump systems, a handful of design iterations have been applied to the model. These changes aim to offer further insight into the measures that may need to be taken to improve or ensure feasibility of the lower temperature heat pump systems.

Two iteration types have been identified; a non-invasive improvement that increases energy consumption, and an invasive retrofit measure that decreases energy consumption.

The first of these iteration is increasing the operating times of the heating system. The heating schedule as set out in Table 3.3, was altered, and the heating schedule has been extended from 57 hours, to 82 hours a week. Table 3.6 sets out these increased heating hours, that for most part have increased by 2 hours (1 hour earlier till 1 hour later).

Table 3.6. Increase heating hours schedule

Zone Type	**Heating Schedule**	
	Morning	*Evening*
	Weekday	
Zone 1	06:00 – 10:00	17:00 – 23:00
Zone 2	06:00 – 10:00	20:00 – 24:00
	Saturday	
Zone 1	06:00 – 14:00	17:00 – 24:00
Zone 2	06:00 – 10:00	19:00 – 24:00
	Sunday	
Zone 1	06:00 – 23:00	
Zone 2	06:00 – 23:00	

This improvement represents a non-intrusive retrofit measure. As expected, however, this development would come with an increase in energy consumption as the heating system is running for a longer time.

The second iteration to be implemented is one of a simple retrofit. It involved an insulation improvement being made to the cavity walls, and replacing all of the windows of the model with double glazing. This change to the model is predicted to have the opposite effect on the energy consumption, but the price paid in this circumstance is the re-infrastructure and invasive measures needed.

Chapter 4. Results & Discussion

As set out in the Method section of the report, 2 significant criteria by which the results of the entire flat are defined have been highlighted. Each of these criteria as well as an additional means of analysis have been reiterated;

a. The focus of the analysis is the thermal comfort of the model, which has been represented through unmet heating hours between the temperature profiles of the base case system and simulation type being examined. An unmet heating hour can be defined as: An hour, during the heating schedule of the model, that cannot reach the temperature set by the base case system. Anything within the range of 3˚C of the heating set point has been deemed acceptable as 18˚C is still recognised as a comfortable thermal level (Mueller & Palombi, 2016). Any unmet hour that exceeds 3˚C from the heating set point are unacceptable. As important as it was to determine the overall unmet heating hours, it was more invaluable to know the unacceptable unmet heating hours, which sit below 18˚C.

b. The second focal point of the results was overall energy consumption of the model. As a proxy for incurred cost, the energy consumption in kWh indirectly addressed the operational costs in both monetary and emissions values. Considering what has been stated earlier about the cost incurred through decreased COP, this study does not look in such depths into financial calculations, and instead offers energy consumption as a representative to be carried forward. In general, the lower the value of energy consumption, the greater the number of unmet heating hours.

c. The final form of analysis to be undertaken is that of a narrower time period, namely a specific week that challenges the heating system the most. In all circumstances this specific week is, not so coincidentally, the coldest week of the year. As this project is focusing on heating capabilities, this specific week highlights, and scrutinise the system intensely.

The main influencing factor in all the simulations that is covered in the proceeding chapter is the external climate of Glasgow (lat. 55.8642˚ N, 4.2518˚ W). ESP-r comes with pre-existing and accurate climate data, which effects indoor temperatures depending on the ambient temperature, solar irradiance, wind speed and direction, and most importantly time of year. The main consideration to be given to the climate is that the majority of heating required, unmet hours sustained and energy consumed occurs during winter.

4.1. Medium Temperature Heat Pump Results

The primary simulation carried out used a medium temperature heat pump as the heat source. As identified above, heat pumps are capable of producing high supply temperatures, the ΔT35 conditions represents a high temperature heat pump, that can supply temperatures of 60˚C. When compared to the base case system, which has a supply temperature of 90˚C, it is interesting to see how often the medium temperature system reaches the defined comfortable metric of 21˚C. Figure 4.1 highlights the average yearly temperatures achieved from the base case and medium temperature heat pump system and Table 4.1 gives the numerical results of the simulation.

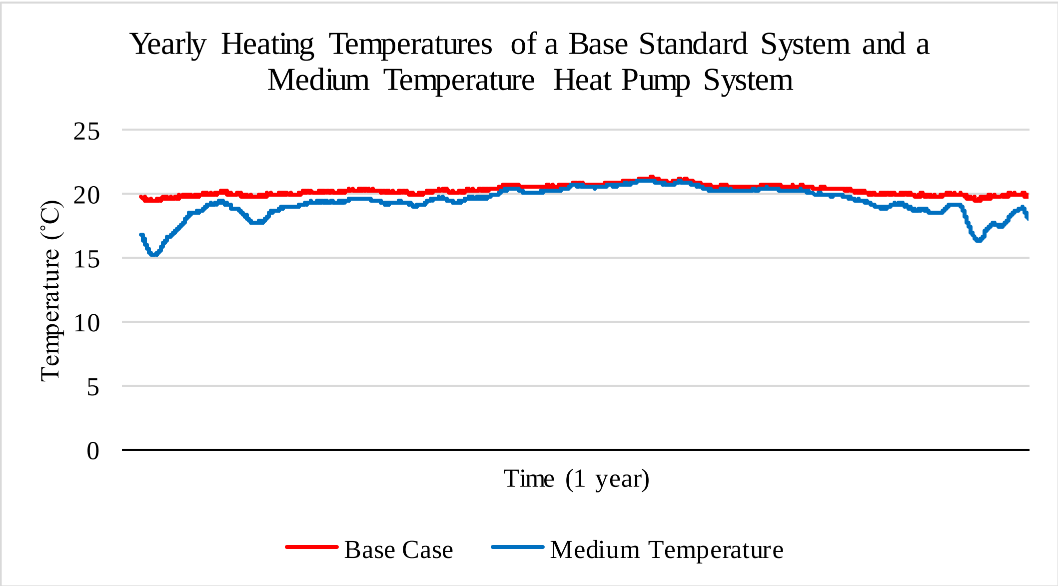

Figure 4.1. Yearly temperature profile of a medium temperature heat pump system against a base case system

Table 4.1. Unmet hours and energy consumption for medium temperature heat pump system

Simulation Type	Number of Unmet Hours 0.5˚C	1˚C	2˚C	3˚C	Below 3˚C	Total	Energy Consumption (kWh)
Medium temperature heat pump	1185	252	379	271	301	2387	**28845**
Medium temperature heat pump on increased heating hours	1545	29	20	10	2	1605	**32718**

From visual analysis, the medium temperature system only manages to attain the comfort level convincingly between April and September. The real deficit in the medium temperature system comes during winter; December, January, February. These times are when the number of unmet hours across the year are most common.

Table 4.1 highlights the results of the simulations from the medium temperature heat pump system. The results present, not only the total number of unmet hours, but also by what degree these unmet hours deviate from 21˚C and considering the limit of acceptance has been set to 18˚C it is appropriate that the detailed analysis starts from here.

The results of the medium temperature heat pump simulation show that a total of 2387 heating hours were unmet across the year, and of these 13% are unacceptable. The largest portion of the unmet hours, 50%, lay within 0.5˚C of the maximum heating temperature of 21˚C.

The energy consumption of this system was calculated to be 29000 kWh. The energy consumption for the base case system, although not stated, comes to just over 30000 kWh across the entire year. Therefore, the reduction of around 1000 kW has created 2387 unmet heating hours.

To raise the number of unmet hours to an acceptable standard (above 18˚C) the first alteration outlined in Iterations Performed, increased heating hours, has been applied to the model. This low impact and easily achieved measure increased the yearly heating hours from 2964 to 4264.

This modification to the model facilitated a drop in the unmet hours by 33% to 1607 unmet heating hours. Of these unmet hours, only 2 hours can be found below 18˚C and 96% of unmet heating hours are within 0.5˚C of the maximum heating set point, 21˚C. This improvement to unmet heating hours has come at the cost of a 13% rise in energy consumption. Now, almost 33000 kWh are being used to power the medium temperature system.

Figure 4.2 gives a closer inspection of the results by examining a thermally challenging week within the year-long simulation. The coldest week (5th – 11th January) shows the only two hours that the medium temperature system on increased heating hours drops below 18˚C.

Visual inspection shows that the medium temperature system alone only just manages to reach 15˚C on the Thursday night and then fails to reach that temperature through to the Friday morning. The addition of the 25 extra heating hours within that week raise the indoor temperature to above 18˚C for all but two hours, and even for these two hours the temperature only drops a fraction below 18˚C.

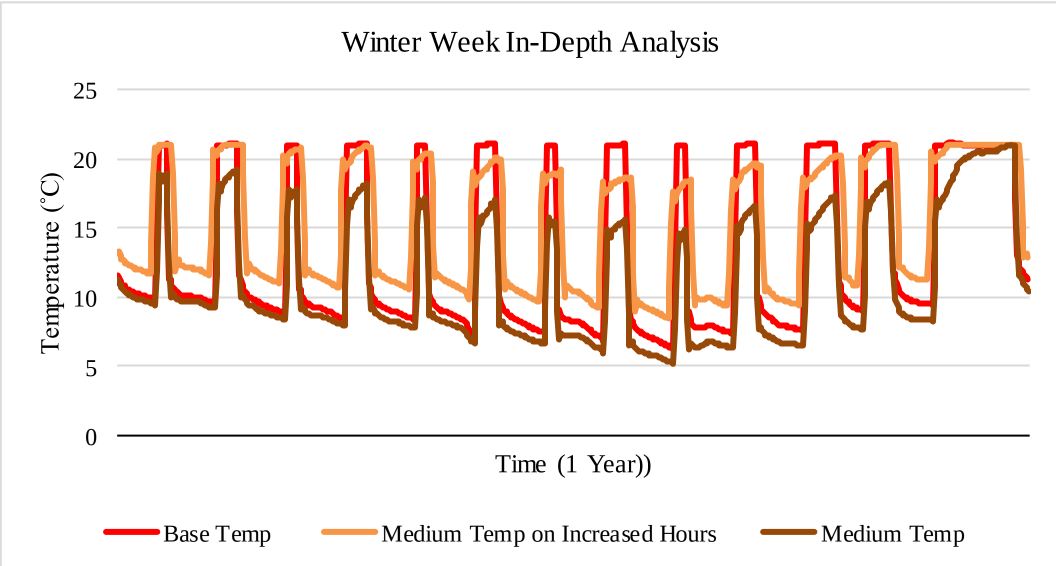

Figure 4.2. Winter week analysis of both medium temperature heat pump systems

Despite the 3000 kWh increase in energy consumption, the medium temperature system with increased heating hours, has managed to mitigate all but 2 unacceptable unmet heating hours. The system has achieved this without the implementation or integration of re-infrastructure. The wet heating system that already exists within the model is capable of achieving and maintaining an acceptable thermal environment while being supplied by a medium temperature heat pump.

4.2. Low Temperature Heat Pump Results

Concluding that the addition of some extra heating hours made the medium temperature heat pump system feasible, it was decided that more harsh conditions should be opted for. The low temperature heat pump system represents a drive towards even more harsh conditions of heating, at the benefit of decreased energy consumption and improved performance efficiency: But at what cost?

The low temperature in this model would be represented through a ΔT15 operating condition, bringing the supply temperature down to 40˚C and further reducing the thermal capabilities of the heating system within the model. Figure 4.2 sets out the temperature profile of the low temperature heat pump system against the base case simulation. Similar to the results presented for the medium temperature system, Table 4.2 highlights the results of the low temperature heat pump system.

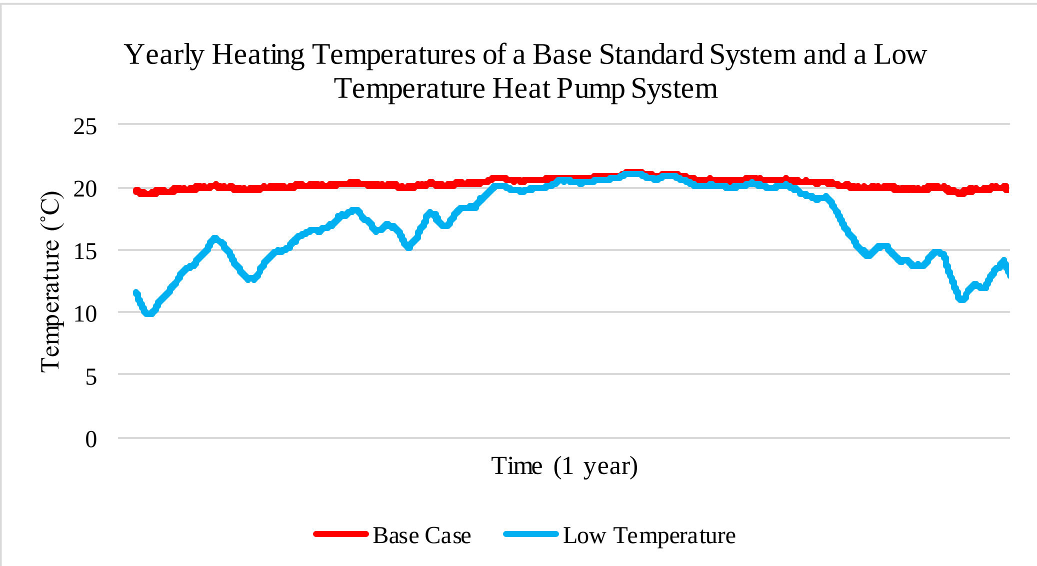

Figure 4.3. Yearly temperature profile of a low temperature heat pump system against a base case system

Table 4.2. Unmet hours and energy consumption for low temperature heat pump system

Simulation Type	Number of Unmet hours						Energy Consumption (kWh)
	0.5˚C	1˚C	2˚C	3˚C	Below 3˚C	Total	
Low temperature heat pump	731	159	273	313	2258	3732	**18438**
Low temperature heat pump on increased heating hours	900	191	404	335	1158	2988	**25192**
Low temperature heat pump with retrofit measures	842	198	331	338	1340	3048	**15456**
Low temperature heat pump on increased heating hours with retrofit measures	1106	188	331	259	530	2414	**22069**

In reducing the inlet temperature from 60˚C in the medium system to 40˚C in the low temperature heating system there are some obvious discrepancies in unmet hours. These can be seen in both Figure 4.3 and Table 4.2. The number of unmet hours of the low temperature heat pump jumps to a total of 3732 out of 4264 heating hours. Of these 3732 unmet hours, 2258 hours sit lower than the acceptable 18˚C. This means that more than half, 60.5%, of all unmet hours are unacceptable, immediately highlighting the reduced feasibility of the low temperature system within the model.

The energy consumption of the low temperature system requires only 18438 kWh across the year to provide what heating capacity it has. This is a 40% drop in energy used and therefore cost incurred. However, the inability of the low temperature system to make even half of the required heating hours means that no matter how low the energy consumption, it is not feasible.

To encourage the low temperature system to achieve more acceptable unmet hours within the model the design iterations mentioned have been implemented.

The primary iteration made mimicked the changes made in the medium temperature heat pump system. An increase of 25 hours of heating a week were implemented and the system simulated again.

This time 2988 unmet hours were recorded, 1158 of which were below acceptable level. Not only is this a 20% drop in unmet hours, but it is a shift to only 38% of those unmet hours now lying outside of 18˚C. Therefore, what can be observed overall is a greater number of unmet hours within the 0.5˚C, 1˚C, 2˚C and 3˚C ranges of unmet hours than in the low temperature system alone.

This improvement to unmet heating hours has however come at the cost of an increased energy consumption. With a 37% increase in overall energy consumption, it seems as though every 1% gained in acceptable unmet hours, has resulted in a 1% energy consumption rise.

Due to almost a third of all unmet hours being under and acceptable level, the low temperature heat pump system operating on increased heating hours, is still not a feasible option for heating the model of the tenement.

To address the issue of energy consumption at the same time as addressing unmet hours, the second iteration type of retrofit was implemented into the model and the heating hours return to the original schedule.

The results from Table 4.2 show that through implementing retrofit measures into the model the energy consumption relative to the low temperature system by itself performs better. The overall yearly energy consumption decreased from 18438 kWh to 15456 kWh.

Not only have the retrofit measures impacted the energy consumed but also the unmet hours. The total unmet hours decreased from 3732 to 3048, which is a smaller reduction than that caused by increasing the operating hours of the heating system. This same relationship is reflected in the proportion of acceptable to unacceptable hours in both the increased heating hours and retrofit simulations. This can be seen in Table 4.3, which gives a summary of the results found in Table 4.2.

Table 4.3. Acceptable against unacceptable unmet hours

Simulation Type	Total Acceptable Unmet hours	Total Below Acceptable Unmet hours	Total Unmet hours
Base vs Low Temperature System	1475	2258	3732.25
Base vs Low Temperature System on Increased Heating Hours	1830	1158	2987.75
Base vs Low Temperature System with Retrofit	1709	1340	3048.25

Within the results, the below acceptable unmet hours are more important than the acceptable, as they represent the systems absolute inability to achieve a comfortable level. For this reason, the most valued improvement is the one that results in the least unacceptable unmet hours. In this case, the increased heating hours simulations mitigates more unacceptable unmet hours, as well as more unmet hours in total. Therefore, the retrofit measures are less feasible than the increased heating hours, even considering the increase in energy consumption.

Relating this back to the focus of the study, despite the low temperature system being unfeasible, the fact that the un-intrusive improvement of increasing heating hours is more effective than the re-infrastructure of a retrofit, means increasing energy supply efficiency can precede dwelling upgrade in tenements.

The final simulation carried out, to determine whether low temperature heat pump systems were feasible at all, included a combination of retrofit and increased heating hours. Referring to Table 4.2 and Table 4.3, the results of this simulation can be seen.

The result of combining the iterations has the greatest impact on unmet hours out of all three of the low temperature heat pump system simulations. The number of unmet hours decreased to 2414, and only 530 of these unmet hours lie below 18˚C. This means that of the 4264 hours that the low temperature heating system is in operation, only 12% of these are unmet to a non-satisfactory degree.

The other impact of the combined system is the effect on the energy consumption. Not as low as the retrofit system alone, and not as high as the increased hours system, the combination simulation has a yearly energy consumption of 22069 kWh. This is a 20% rise in energy consumption compared to the low temperature system alone.

Despite the results obtained by combination simulation, there is still a deficit in heating hours met. A more in-depth analysis of a week in winter has been carried out and presented in Figure 4.4 to help establish the efficacy of all the low temperature heat pump simulation variations.

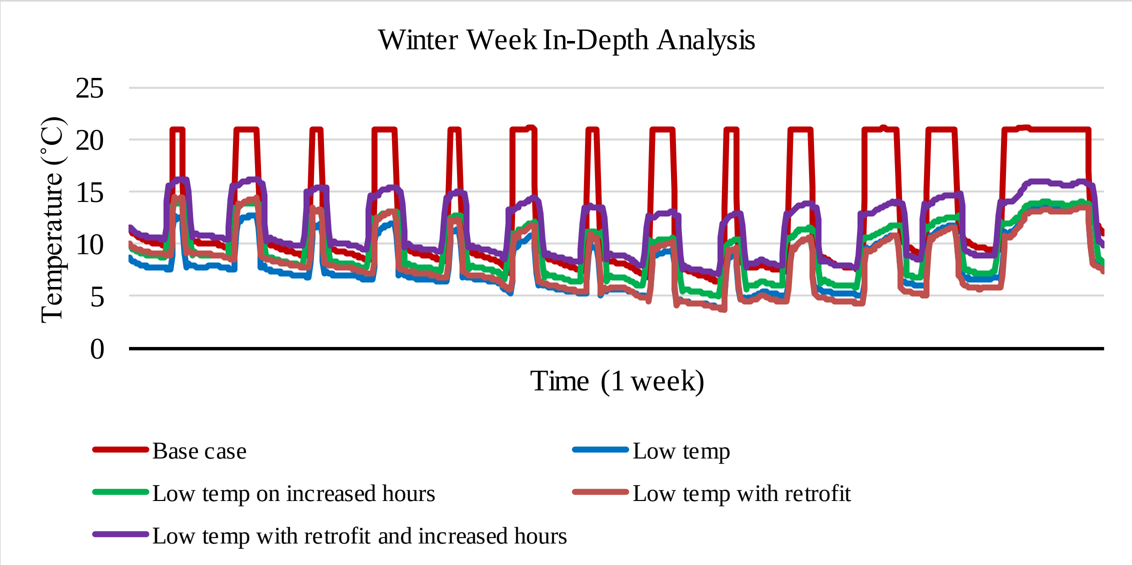

Figure 4.4. Winter week analysis of both low temperature heat pump systems

During the coldest week of the year the low temperature systems have no capability in achieving an acceptable thermal environment. The increase in energy consumption in the increased hours simulation shows a continuous improvement on the low temperature system. The retrofit simulation, although attaining just as high temperatures during the mild days, falls to the same level as the low temperature system on cold days. Finally, the combination of the two improvements has the greatest effect as the system can take longer to ramp up, as well as having increased insulation to help retain heat making the model more energy efficient.

The low temperature heat pump system cannot achieve an acceptable level of thermal environment during the times when heating is necessary. The implementation of retrofit measures has been necessary in enhancing the ability of the low temperature system as much as possible. However, the means that have been deployed to facilitate such improvement are very invasive, cost heavy and difficult to integrate into tenement style housing. Therefore, the use of a low temperature heat pump system, with retrofit measures and a limited increase to heating hours has been deemed not feasible within this archetype of building.

4.3. Low Temperature Minimum Required Heating Hours

A final study focussed on determining how many heating hours it would take for the low temperature to achieve 0 unacceptable unmet hours. This simulation integrated the retrofit measures as well as increasing the heating hours within the model incrementally until the system reached 0 unmet hours below 18˚C or there were no more hours to have the heating on.

It took the low temperature system to be to be on full time, 168 hours a week, to achieve a thermal environment reminiscent of the base case system. However, the 111 hour increase per week was still not enough to achieve 0 unacceptable unmet heating hours (Table 4.4). This can be seen in the winter week analysis shown in Figure 4.5.

Table 4.4. Unmet heating hours in low temperature minimum required

Simulation Type	Number of Unmet hours						Energy Consumption (kWh)
	0.5˚C	1˚C	2˚C	3˚C	Below 3˚C	Total	
Low temperature minimum required heating hours	1529	67	47	20	6	1669	**32347**

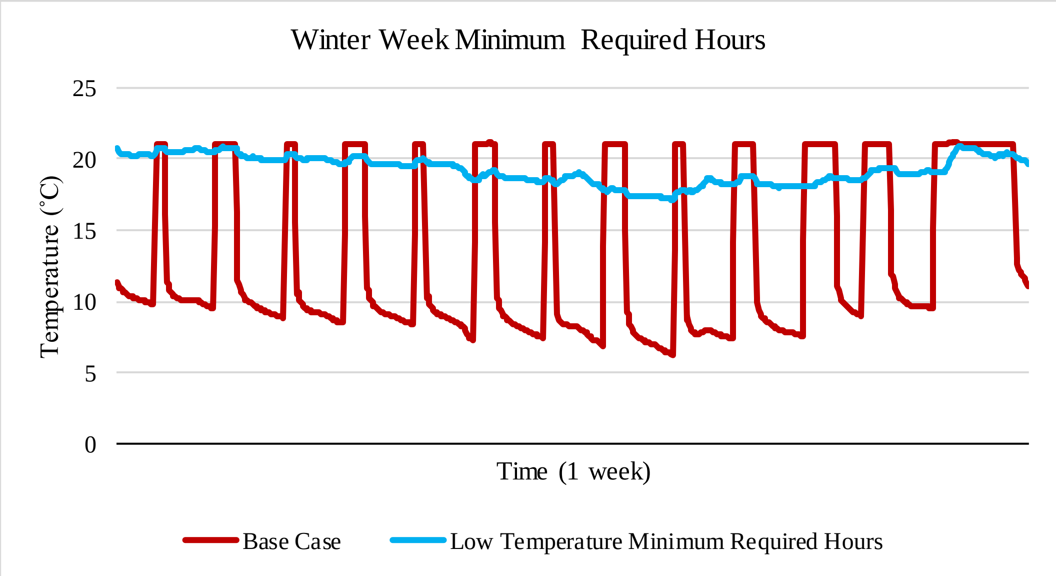

Figure 4.5. Winter week analysis of low temperature heat pump system with minimum required heating hours

The heating in this simulation is on for all 8760 hours a year. However, despite this the system still cannot totally achieve 21˚C. The low temperature system still dips down below 18˚C and because all hours are now being considered as "heating hours", a total of six unacceptable unmet heating hours are identified between Thursday night and Friday morning.

The massive increase in heating hours comes at an energy consumption cost equal to that of the medium temperature heat pump system, 32347 kWh. From 18438 kWh a year in the original low temperature system, the energy consumption increased by 75% and still the system was not capable of 0 unacceptable unmet heating hours. Therefore, it can be determined that it is unfeasible to integrate a low temperature heat pump system into a tenement flat without the need for intense re-infrastructure and retrofit.

4.4. Summary of Results

A range of results have been presented within this section of the report that help answer the question, can lower temperature, lower energy consuming heating system stand up to a base case gas-fired boiler? However, the results of this study do not address the complete picture. There are other aspects of energy retrofitting and dwelling retrofitting that hold equal value to these results.

As well as the results presented in the above chapter, individual zone results can be found in "Appendix X – Zone 1 Results", and "Appendix XI – Zone 2 Results".

The Social Impact of Retrofit

For the simplicity of the study and the alterations to the model parameters, only basic retrofits were implemented, and this project only happen to target an individual flat. However, in a real-life situation outside of the model, retrofits within tenement buildings tend to be more complex and retrofitting starts to become more of a social issue than a cost one. The addition of completely new heating infrastructure for a decentralised heat source becomes an issue that not only involves a single flat, but the whole close of the building (4-8 flats). The social aspect of this comes in trying to convince all resident of that close to be relocated while their homes are stripped back and re-piped, refurbished and upgraded. The logistics of achieving this are very difficult and the benefits of such a project have to strongly outweigh the negatives in order for it to be a worthwhile investment.

A study similar to this was carried out by John Gilbert Architecture in Milnbank, Glasgow where the feasibility of upgrading tenements in energy efficiency to meet Passivhaus standard was investigated (John Gilbert Architecture, 2013). It was found that achieving Passivhaus standards in the refurbishment of old buildings was very challenging. But upon carrying out three different standards of retrofit (bronze, silver and gold) some conclusions were presented:

- Retrofitting is better addressed close-by-close instead of flat-by-flat.
- The strategies of improving airtightness had a greater effect on energy use than just insulation alone.
- Decentralised heating has a larger impact on cost of heating over energy usage reduction.
- The flat position with respects to the close has a large impact on the cost of retrofit.

- The cost involved in any of the refurbishments carried out is significant. Despite Milnebank already having addressed many 'quick fix' issues.

Some of these conclusions are very impacting on the project in hand, in that they highlight how refurbishment is better done on a grander scale, decentralised heating systems see more impact on cost over energy usage and that any cost included is going to be significant.

Relating these findings back to the project, shows how desirable it might be to integrate a new heating system without the need for extensive or intrusive measures. Within this study, it has been shown that it would be impossible to implement a low temperature input system without carrying out at least some forms of basic retrofit first, and that is where the social aspect would stall or completely halt this development. However, the medium temperature input system, implementing the same installation methods highlighted in the South Seeds study, as can be seen in Figure 4.6, needs no intrusive retrofit measures to meet a satisfactory heating level (South Seeds, 2016). This makes the medium system a very plausible option for the implementation within tenement flats.

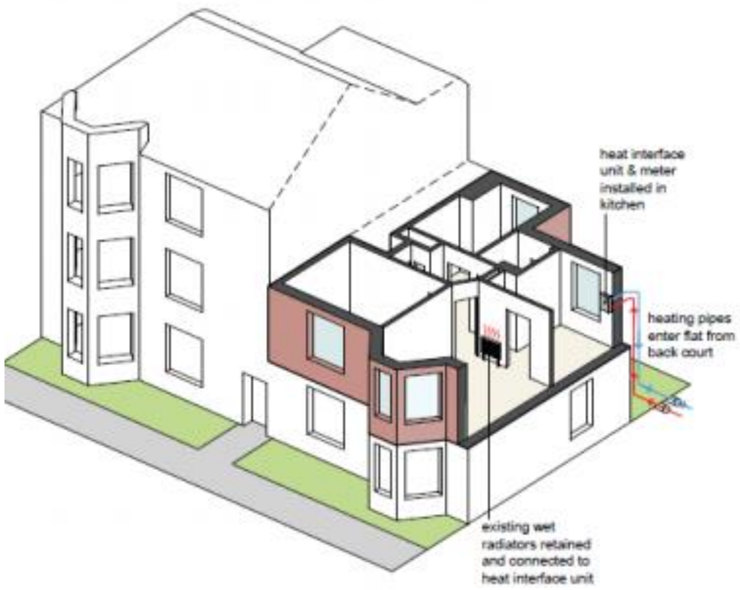

Figure 4.6 District heating integration in tenement flats (South Seeds, 2016)

Chapter 5. Conclusion

The Scottish government has set out a "Satisfactory Heating Regime" for vulnerable and non-vulnerable house-holds (Mueller & Palombi, 2016).

"The Satisfactory Heating Regime is defined as: For vulnerable households, 23˚C in the living room and 18˚C in other rooms, for 16 hours in every 24. For other households, this is 21˚C in the living room and 18˚C in other rooms for 9 hours a day during the week and 16 hours a day during the weekend."

Other proposals for comfortable metrics have been suggested by different establishments, such as The National House Building Council (NHBC), who recommend temperatures depending on the room type: Dining room, living room and bedroom should all be maintained at 21˚C; kitchen, utility and cloak rooms only require 18˚C; and finally, the bathroom should be kept at 22˚C (Stelrad, 2017).

Following the rough guideline of comfort from these sources, conclusions of the current study have been drawn.

Through carrying out a variety of simulations and iterations on a model created to emulate a tenement flat, the question of whether a low temperature heat pump can replace a base case boiler whilst avoiding the need for complete re-infrastructure has been answered.

The results show that 61% of all heating hours throughout the year are unmet by a low temperature heat pump, making this system completely unfeasible. With retrofit measures and increased heating hours implemented the low temperature system still cannot achieve 0 unacceptable unmet hours. The use of intrusive retrofit measures, alongside the inability to achieve all acceptable unmet heating hours, allows for the low temperature heat pump system to be ruled out as a heating option for tenement flats.

Similar simulations were carried out using a medium temperature heat pump system. Without alteration, only 10% of heating hours fell below 18˚C. Yet, when simple operational details such as heating times were increased the medium temperature unmet heating hours dropped to only 2 out of 4264 heating hours dropped below 18˚C.

However, this was achieved at an energy incursion of 3873 kWh, making the yearly consumption 32718 kWh. Accepting the increase in energy consumption, the medium temperature system has been shown to be capable of meeting heating demand without the need for retrofit or re-infrastructure, which was the aim of the project. The medium temperature heat pump system under increased heating hours can therefore be deemed a feasible low temperature and sustainable option for tenement flats.

5.1. Limitations to the Project

The main limitations within the project were the difficulties encountered during the modelling stage. The time spent creating the model of a tenement flat very much impacted the overall time given to the project. Although very important and very detailed, the modelling phase of the project accounted for 20-25% of the time spent on the study. This included time taken to research appropriate literature that identified key parameters and aspects of tenements, time spent plotting geometries of the chosen building and time spent integrating all the construction and operational details.

5.2. Future Work

The natural progression of this project beyond the point to which it has been taken, would be the inclusion of not just one, but all other building archetypes. This project covered only pre-1919 Glasgow tenement flats. As highlighted throughout the report, there are many different style of tenement flat thatproceed pre1919 tenement flats, and progress through to post 1982.

Tenements are not the only style of building either, there are a vast number of different residential building types; semi-detached, detached, terrace, bungalow. There are also an even greater number of non-domestic building types that require alternative, clean, green and renewable space heating solutions as well.

The current study addresses the problem identified on 2 significant criteria; unmet heating hours and energy consumption. A future project might extend these criteria to include emissions involved. This would consider the emissions produced by the heat pump and district heating, as well as the emissions mitigated through improvements made.

The ideal end point to this study would be the establishment of a database with a complete set of building archetypes that span the Scottish building stock, that include suggestions and studies into;

- Which heating solutions are feasible and which are not.
- How much they will cost.
- The impact they will have on the environment.
- The degree of alteration that may need to be carried out to make these heating systems feasible.
- The costs related to those alterations within that archetype.

5.3. Final Remark

The Scottish Government's satisfactory heating regime suggests that a non-vulnerable home should be kept at 21˚C in the living room and 18˚C in all other rooms for 9 hours a day. This modelling study has provided results that determine that a low temperature heat pump cannot achieve these requirements without extensive re-infrastructure. However, with simple alterations to the heating schedule it is possible that a medium temperature, ΔT30, heat pump system can achieve an acceptable thermal environment whilst avoiding re-infrastructure.

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Appendices

Appendix I – Thermal Comfort

A basic definition of thermal comfort comes from ASHRAE (1966), which suggests:

> *"Thermal comfort is that condition of mind which expresses satisfaction with the thermal environment".*

Human comfort is affected by six rudimentary factors. These factors include; Metabolic rate (the energy which the body generates given by Metabolic rate - External Work); Clothing Insulation, quantity of clothing being worn; Air Temperature; Radiant Temperature, which is calculated as an average temperature of the surrounding surfaces; Air Velocity, rate of air movement over a surface for a designated period of time; and Relative Humidity, which is the water vapour percentage in the air (Parsons, 2010).

It was not until 1970, when Fanger established a method as well as principles of evaluation and analysis of thermal environments, which would lead to results regarding thermal comfort. Fanger recognised that is was a combination of all physical factors that contribute to thermal comfort. He formulated an equation, that was based around 4 conditions for a person to be in thermal comfort:

- The body being in heat balance
- Sweat rate is at a comfortable level
- Mean skin temperature is within comfortable range
- Absence of local thermal discomfort (draught or air movement)

Equation 1 uses only the six basic influencing factors and the conditions highlighted above, to calculate levels of thermal comfort.

$$H - E_d - E_{sw} - E_{re} - L = K = R + C \text{..........Equation 1}$$

Where:

H	=	Internal heat produced in the human body
E_d	=	Heat loss by water vapour diffusion through skin
E_{sw}	=	Heat loss by evaporation of sweat from skin surface
E_{re}	=	Latent respiration heat loss
L	=	Dry respiration heat loss
K	=	Heat transfer from skin to outer clothing surface
R	=	Heat transfer by radiation from clothing surface
C	=	Heat transfer by convection from clothing surface

The human body generates heat, which is then emitted from the upper epidermal layer of the skin and from respiration of the lungs. The heat rising through the surface of the skin is transferred through the clothes and then lost to the environment.

Heat transfer by radiation, convection and conduction are all parameters required to calculate the thermal comfort of an individual. A 'cold' sensation can be described to when the heat which is leaving an occupant is greater than the heat being generated. Alternatively, when the heat being generated or radiant heat is more than that being expelled, the occupant will be in the warmer side of comfort.

Predicted Mean Vote (PMV)

To evaluate thermal environments, Fanger created a scale of thermal comfort. The degree of comfort would depend on the thermal load (L), which would be the difference between heat production and heat lost to the environment of a man at average skin temperature and activity levels. Comfort would be defined as 0, and the degree of thermal discomfort would be a function of thermal load and activity levels. The result of the function across a large group of individuals would be the predicted mean vote (PMV).

PMV is a widespread approach that enables the analytical determination and interpretation of thermal comfort. The ISO Standard 7730:2005 (ISO, 2005), recognises PMV and predicted percentage dissatisfied (PPD) as useful and easy to apply methods to establishing thermal comfort and discomfort. Fanger uses Equation 2 to calculate the PMV presented in the following table (Fanger, 1970).

Sensation	PMV
Hot	+3
Warm	+2
Slightly warm	+1
Neutral	0
Slightly cool	-1
Cool	-2
Cold	-3

$$PMV = 0.303e^{-0.036M} + 0.028 \times [(M-W) - 3.05 \times 10^{-3}\{5733 - 6.99(M-W) - p_a\} - 0.42\{(M-W) - 58.15\} - 1.7 \times 10^{-5} M(5867 - p_a) - 0.0014M(34 - t_a) - 3.96 \times 10^{-8} f_{cl}[(t_{cl} + 273)^4 - (t_r + 273)^4] - f_{cl}h_c(t_{cl} - t_a)\}] \text{..........Equation 2}$$

And;

$$f_{cl} = 1.0 + 0.2I_{cl} \; for \; I_{cl} \leq 0.5$$

$$f_{cl} = 1.05 + 0.1I_{cl} \; for \; I_{cl} > 0.5$$

$$t_{cl} = 35.7 - 0.0275(M-W) - R_{cl}\{(M-W) - 3.05[5.73 - 0.007(M-W)p_a] - 0.42[(M-W) - 58.15] - 0.0173M(5.87 - p_a) - 0.0014M(34 - t_a)$$

$$R_{cl} = 0.155I_{cl}$$

$$h_c = 12.1(V)^{0.5}$$

Where;

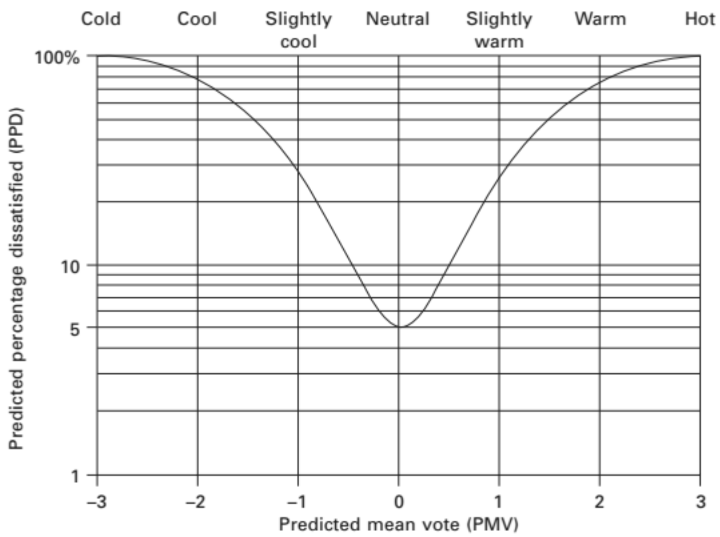
E	Euler's number = 2.718	R_{cl}	Clothing thermal insulation
f_{cl}	Clothing factor	t_a	Air temperature
h_{cl}	Convective heat transfer coefficient	t_{cl}	Surface temperature of clothing (˚C)
I_{cl}	Clothing insulation	t_r	Mean radiant temperature (˚C)
M	Metabolic rate (W/m^2)	V	Air velocity (m/s)
P_a	Vapour pressure of air (kPa)	W	External work (Fanger, 1970)

Predicted Percentage Dissatisfied (PPD)

As expected the PPD calculates the percentage of occupants of a room/ dwelling that is uncomfortable in the thermal conditions of the zone. It is function of PMV, because as the PMV result drifts further from 0 as the PPD increases. The maximum number of individuals that can be dissatisfied within a thermal environment is 100%, and as it is impossible to satisfy every single person’s personal thermal comfort levels, an acceptable PPD level at any one time is <10% for a room or space (ASHRAE, 2010).

PPD can be defined by the following equation and the relationship between PPD and PMV is represented in the figure below.

$$PPD = 100 - 95e^{[-(0.3353PMV^4 + 0.2179PMV^2)]}$$



Adaptive Comfort

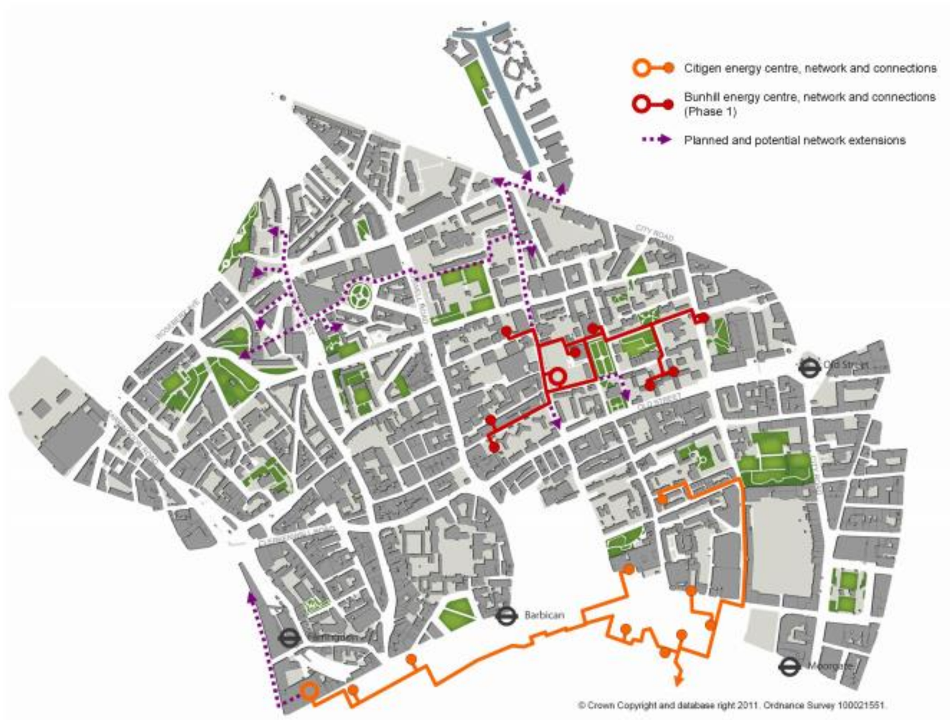
Adaptive comfort models take into account a lot more human behaviour. The model assumes that if a change occurs in the thermal environment, which results in discomfort, then the occupant’s behaviour alters accordingly to re-establish comfort. Actions like; taking off or putting on clothes, reducing activity levels or even opening windows or doors. The function of adaptive comfort models is to facilitate the range of conditions designers can consider as comfortable, especially in naturally or well ventilated buildings where the occupant has much more control over the thermal environment.

Adaptive comfort can only be considered in spaces that have operable windows, not mechanical cooling systems like air conditioning. The occupant must also have relatively low activity levels and have a metabolic rate between 1 and 1.3 met.

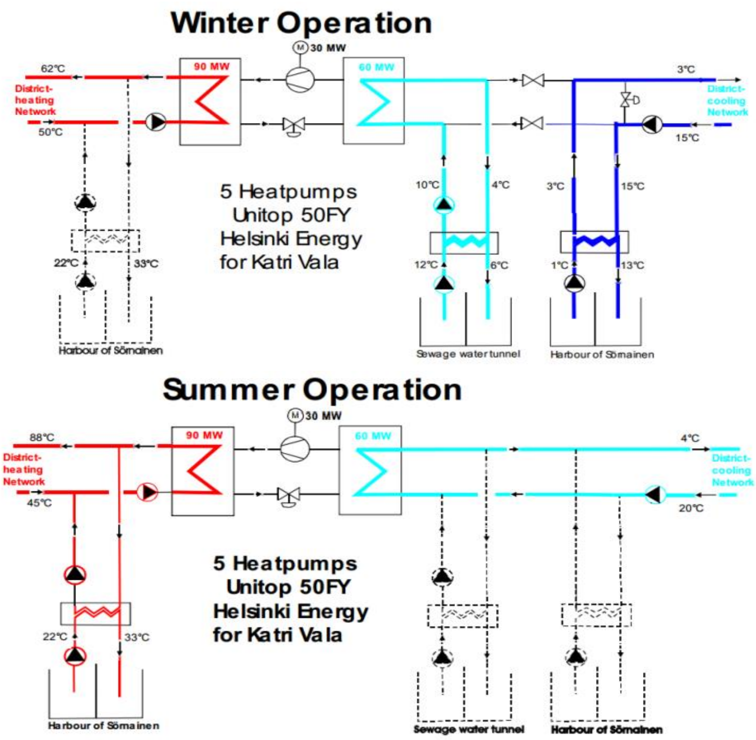
Appendix II – District Heating Piping

Two differing dimensions of piping, junction pipes and valves for University of Strathclyde small scale heat network (University of Strathclyde, 2016).

Appendix III – Islington and Bunhill Heat Network Scheme (Islington Council, 2013)

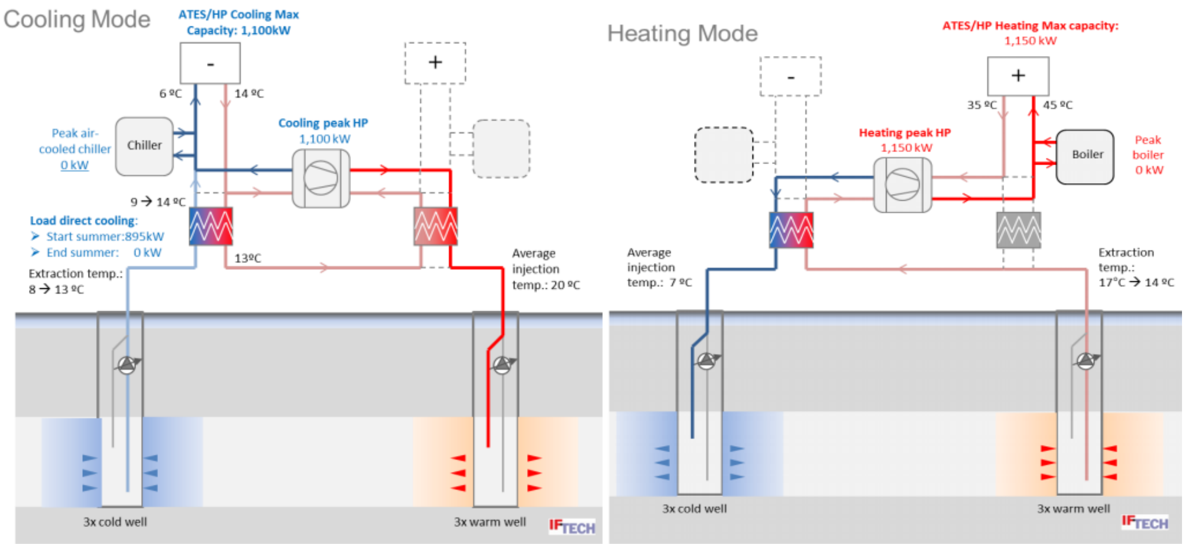


Appendix IV – Helsinki Heat Pump District Heating Scheme Operations (Foster, et al., 2016)



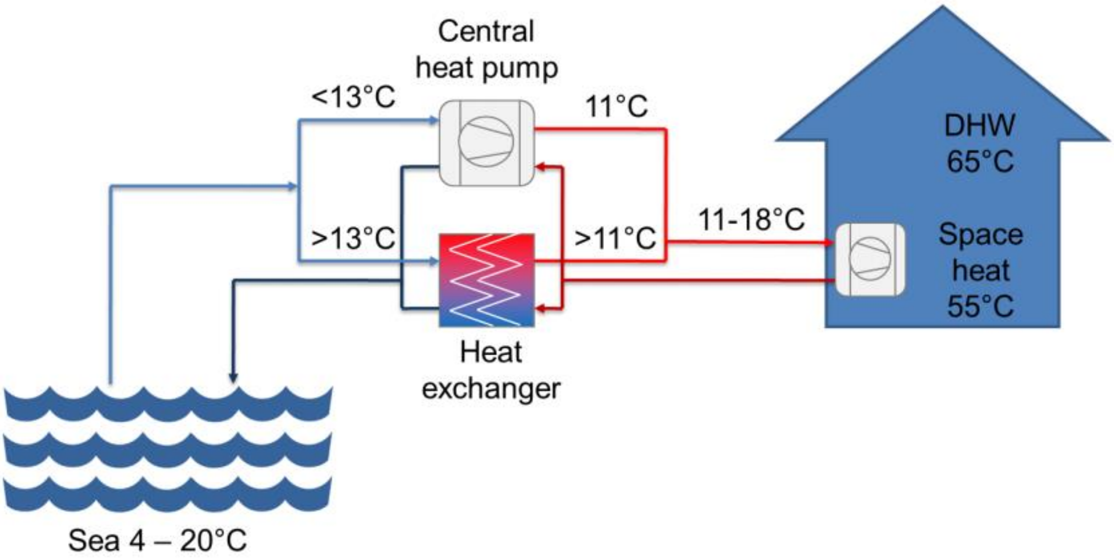
		Winter	Summer
Installed plant	Number of heat pumps	5	
	Refrigerant	R134a	
	Heat pumps used	Friotherm Unitop 50FY	
Heating	Heat supply temperature	62°C	88°C
	Source	sewage	seawater
	Source temperature	10°C	22°C
	Max heat output	83.9 MW	90.6 MW
Cooling	Supply temperature on cold side of heat pump	[not used]	4°C
	Max coolth output	[not used]	60 MW
Performance	COP (heating)	3.51	2.96

Appendix V – Wandsworth Riverside District Heating Operation (Foster, et al., 2016)



		Winter	Summer
Installed plant	Number of heat pumps	3	
	Refrigerant	R134a	
	Heat pumps used	J&E Hall WHP 602	
Heating	Heat supply temperature	45°C	45°C
	Source	aquifer	aquifer
	Source temperature	14°C	16°C
	Max heat output	1.2 MW	N/A
Cooling	Chilled supply temperature	6°C	6°C
	Max cooling output	N/A	2.2 MW
	COP (heating)	Design: 4	N/A
	COP (cooling)	<12	Design: 8

Appendix VI – Duindorp Water Source Heat Network (Foster, et al., 2016)

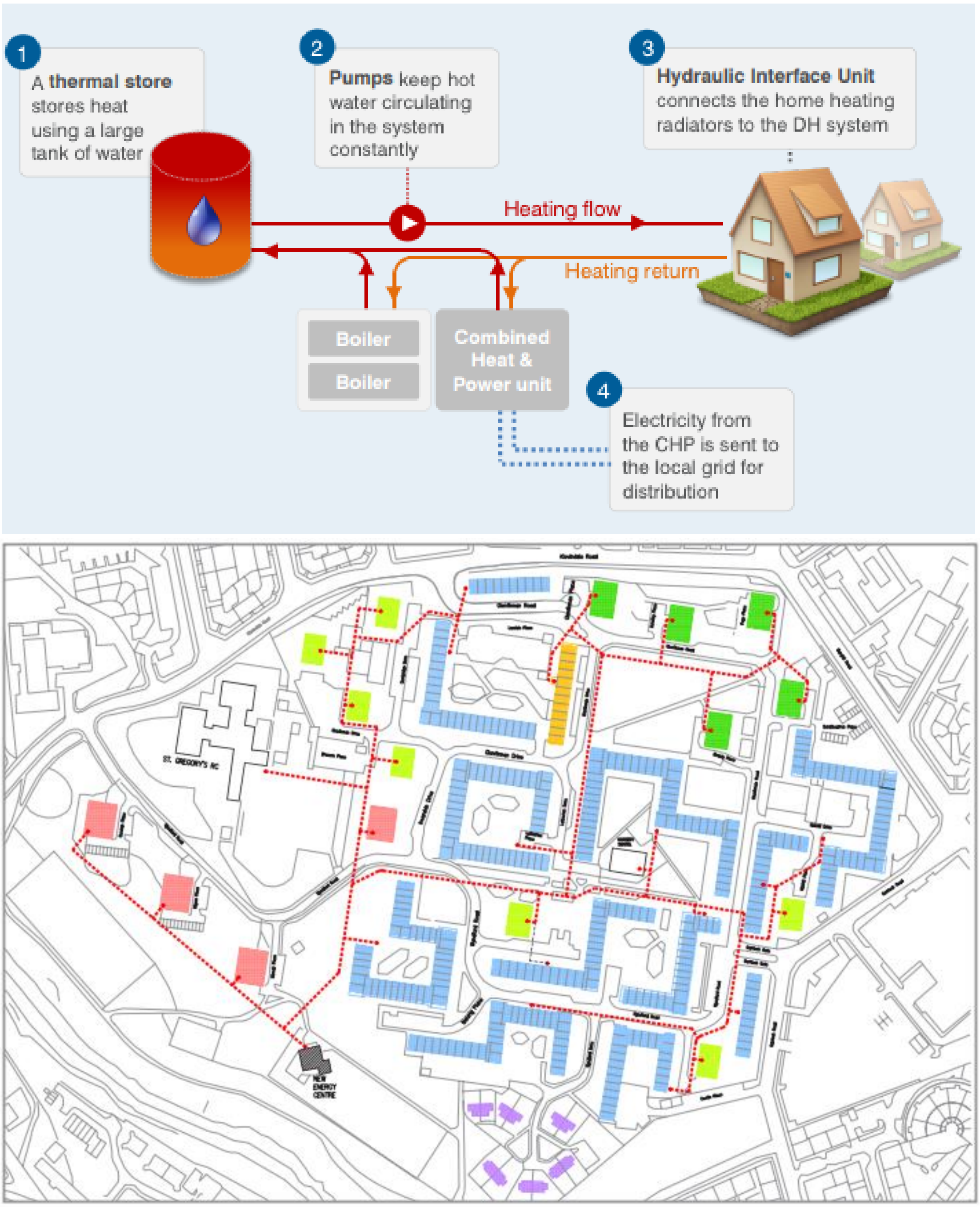


		Central heat pump Winter	Central heat pump Summer	Individual heat pump Year-round
Installed plant	Number of heat pumps	2 central heat pumps		1 per apartment
	Refrigerant	Ammonia		Not known
	Heat pumps used	York PAC 163HR		IVT (no longer in business)
Heating	Supply temperature	11°C	HP not used when sea above 11°C	Underfloor at 45°C DHW up to 60°C
	Source	Seawater	-	District heating network
	Source temperature	3°C	Up to 20°C	11-20°C
	Max heat output	2.4 MW	-	6 kW per apartment
Cooling	Cooling provided	No		No
Performance	COP (heating)	11	Heat pump not used	3

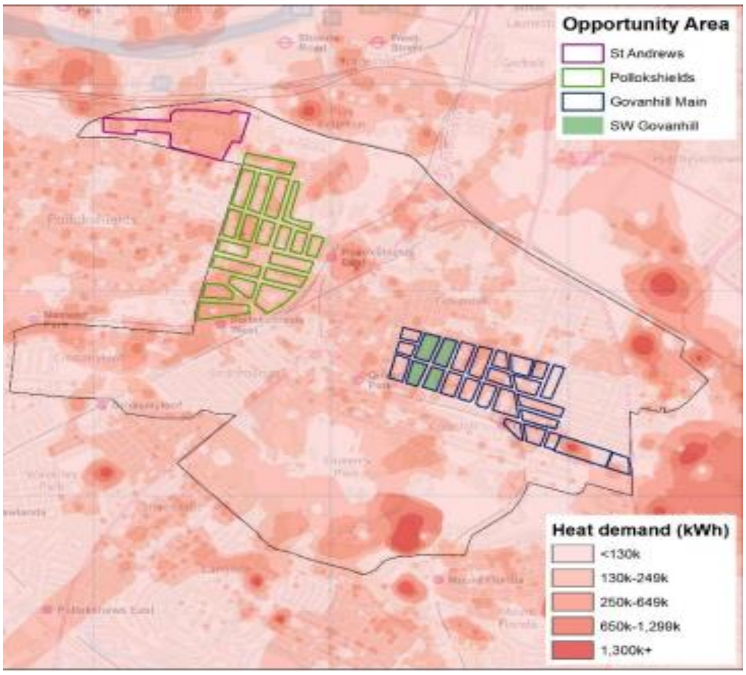
Appendix VII – Brook Street GSHP Network Technical Parameters (Foster, et al., 2016)

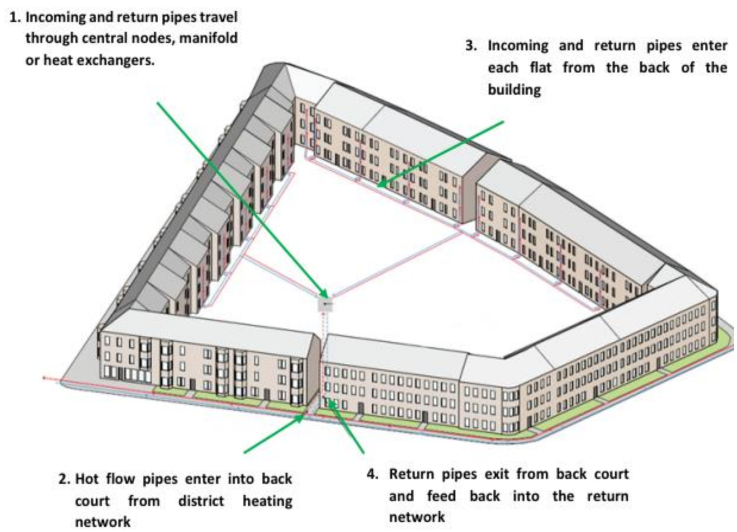
Installed plant	Number of heat pumps	3
	Refrigerant	R134a
	Heat pumps used	Dimplex 40 kW
Heating	Supply temperature	Up to 60
	Source	Ground
	Source temperature	6-10°C
	Max heat output	120 kW
Cooling	Cooling provided	No
Performance	COP (heating)	Design: 3:2

Appendix VIII – Wyndford Estate, Glasgow CHP District Heating Scheme (Parson Brinckerhoff, 2012)

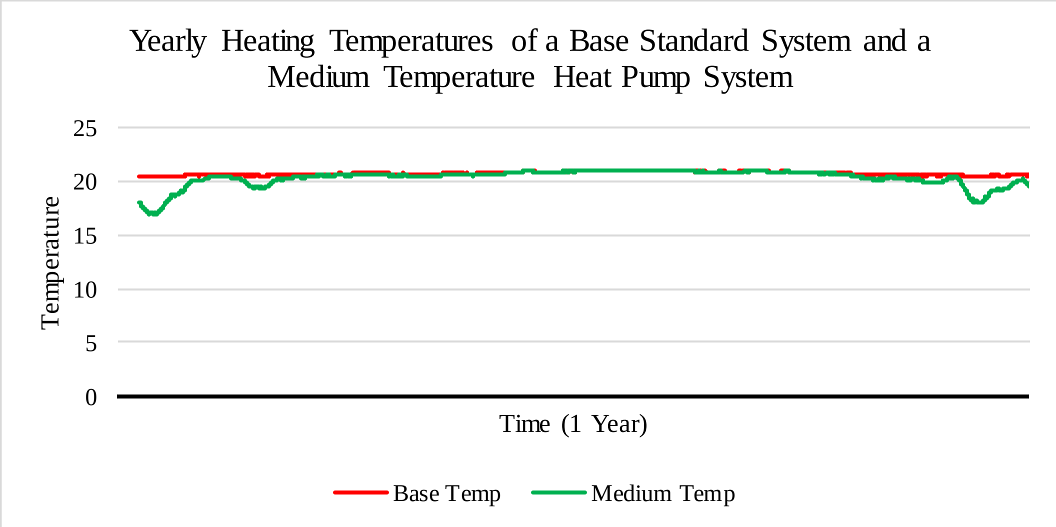


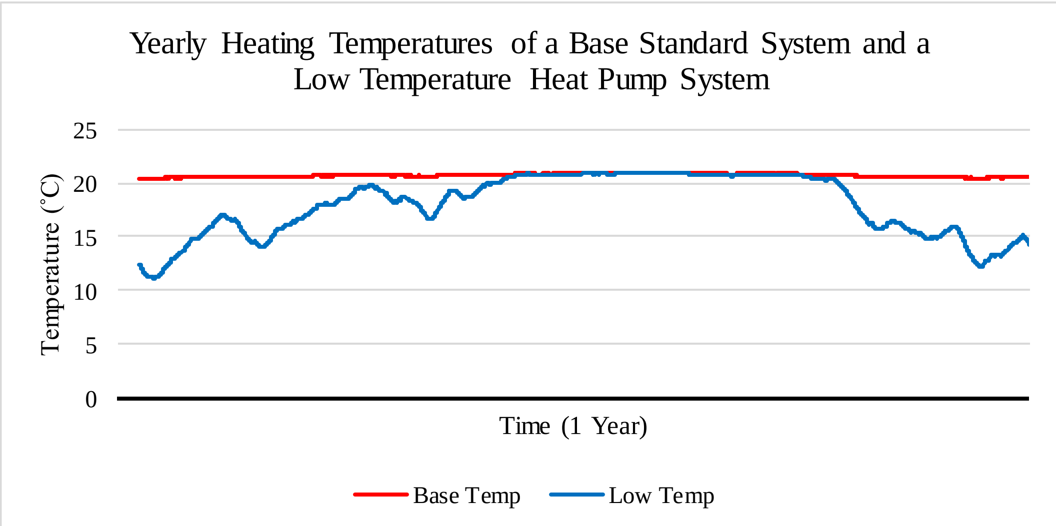
Appendix IX – Govanhill and Pollockshields, Glasgow District Heating (South Seeds, 2016)

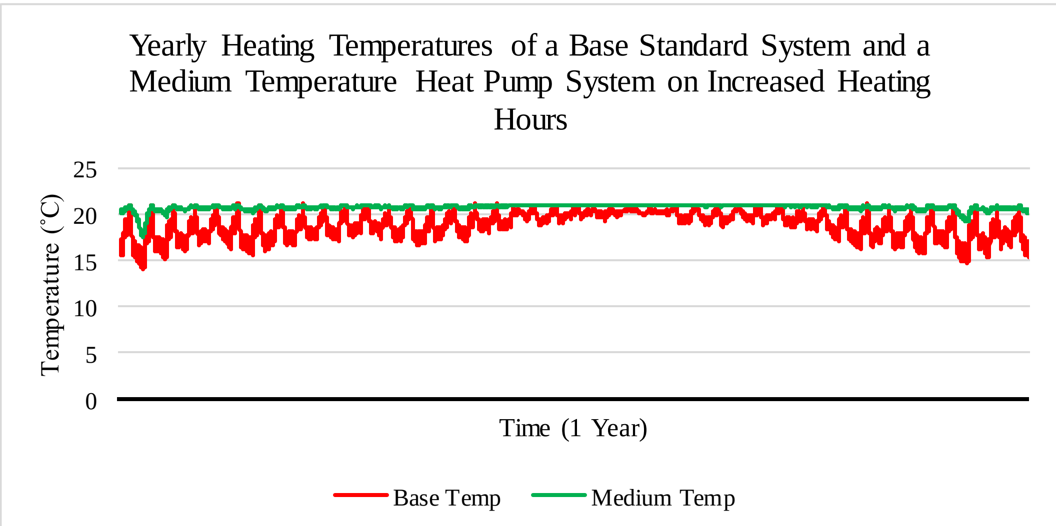


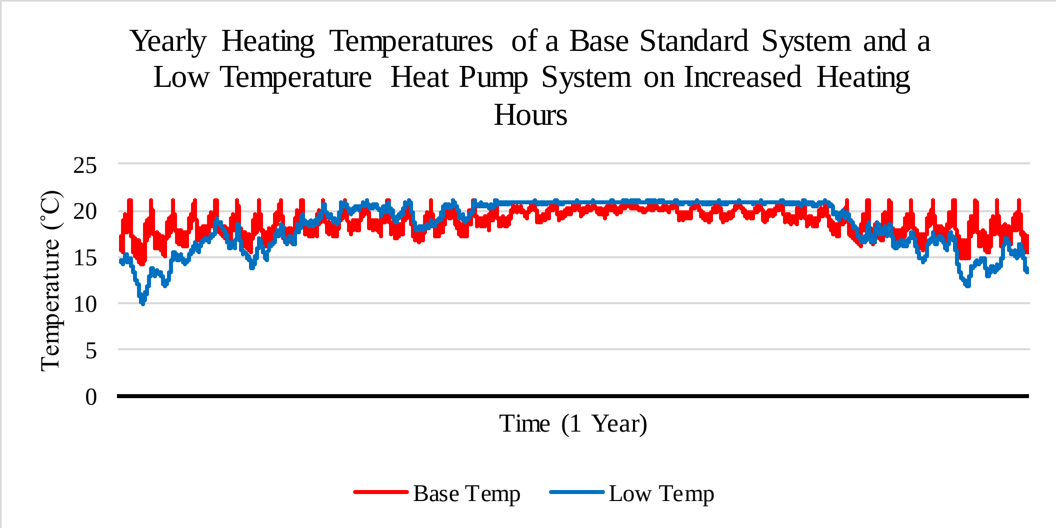


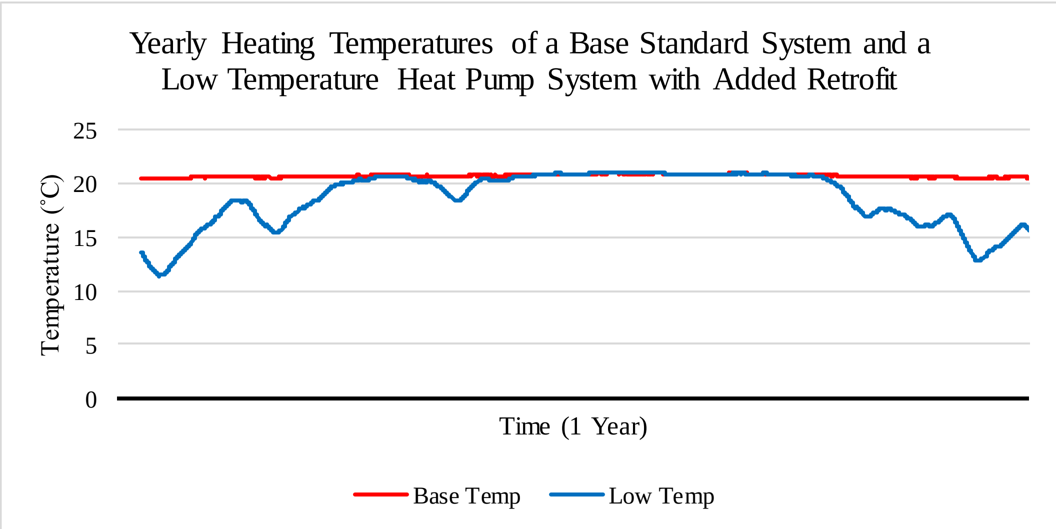
Appendix X – Zone 1 Results

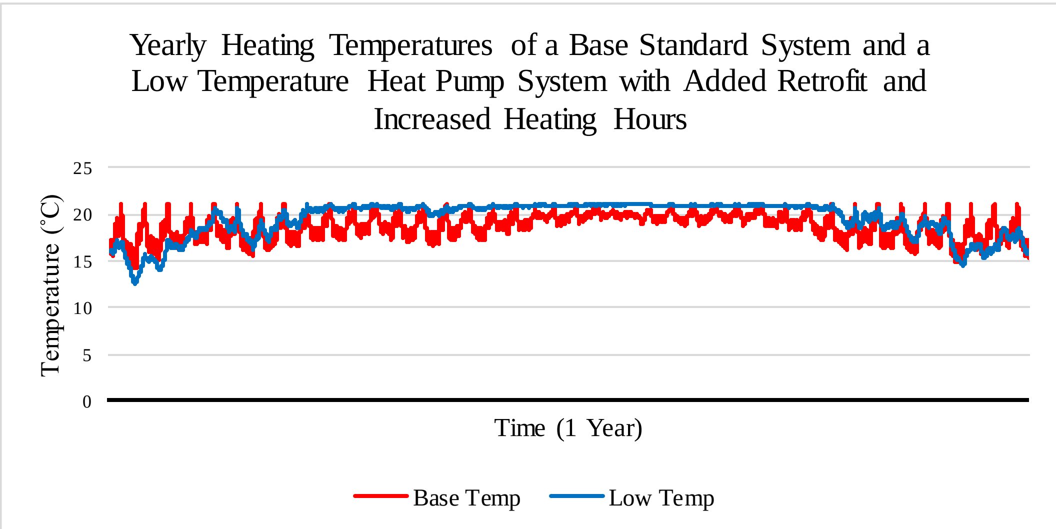




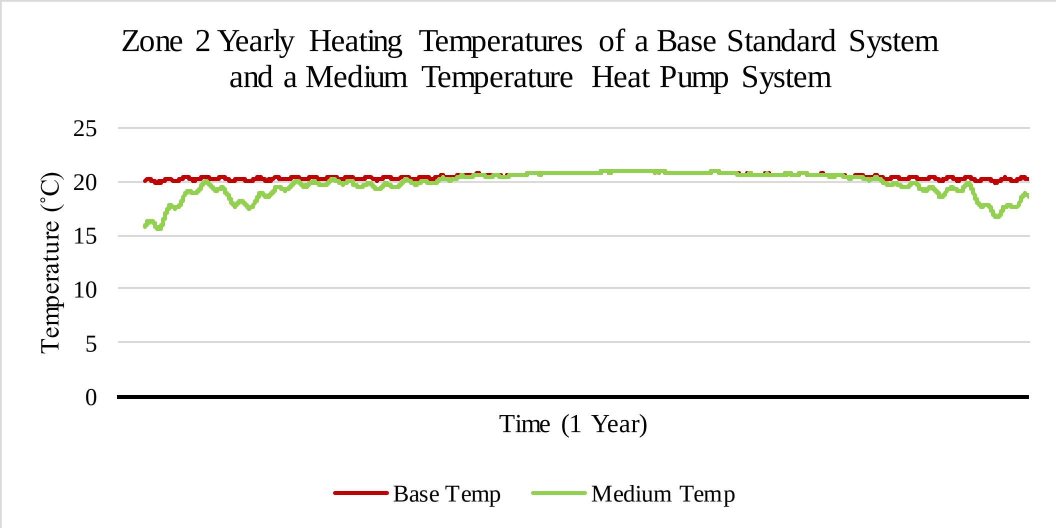


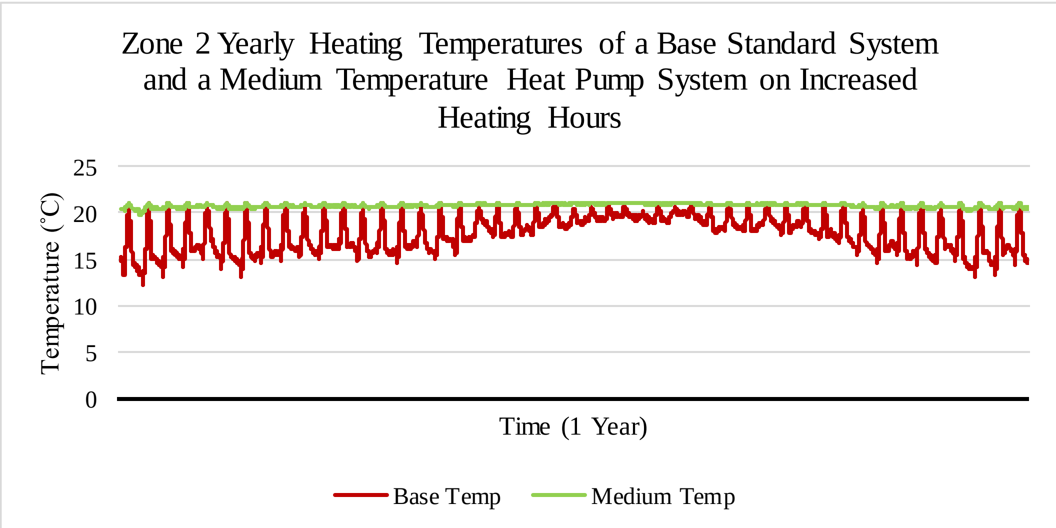

Yearly Heating Temperatures of a Base Standard System and a Low Temperature Heat Pump System on Increased Heating Hours
25
20
15
10
5
0
Temperature (°C)
Time (1 Year)
Base Temp
Low Temp

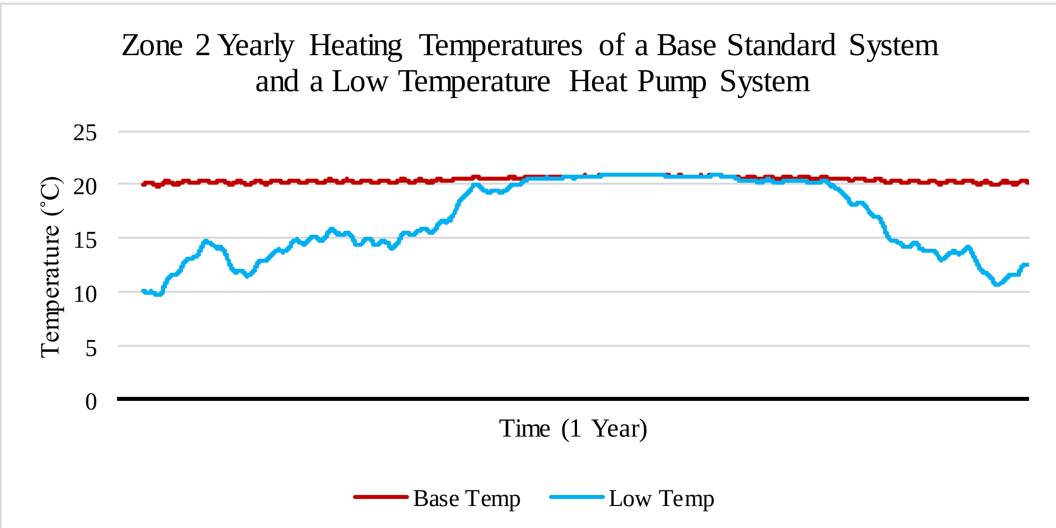

Yearly Heating Temperatures of a Base Standard System and a Low Temperature Heat Pump System with Added Retrofit
25
20
15
10
5
0
Temperature (°C)
Time (1 Year)
Base Temp
Low Temp

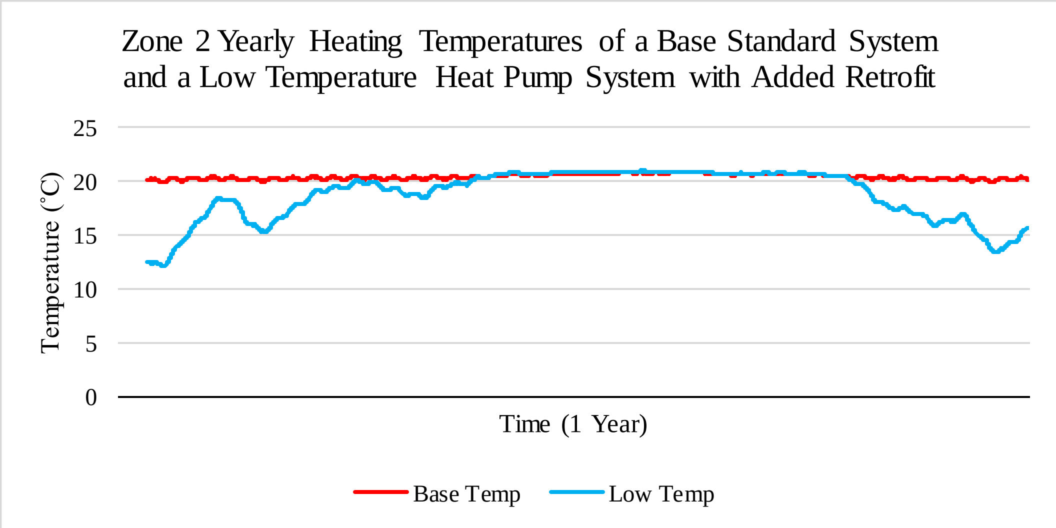

Yearly Heating Temperatures of a Base Standard System and a Low Temperature Heat Pump System with Added Retrofit and Increased Heating Hours
25
20
15
10
5
0
Temperature (°C)
Time (1 Year)
Base Temp
Low Temp

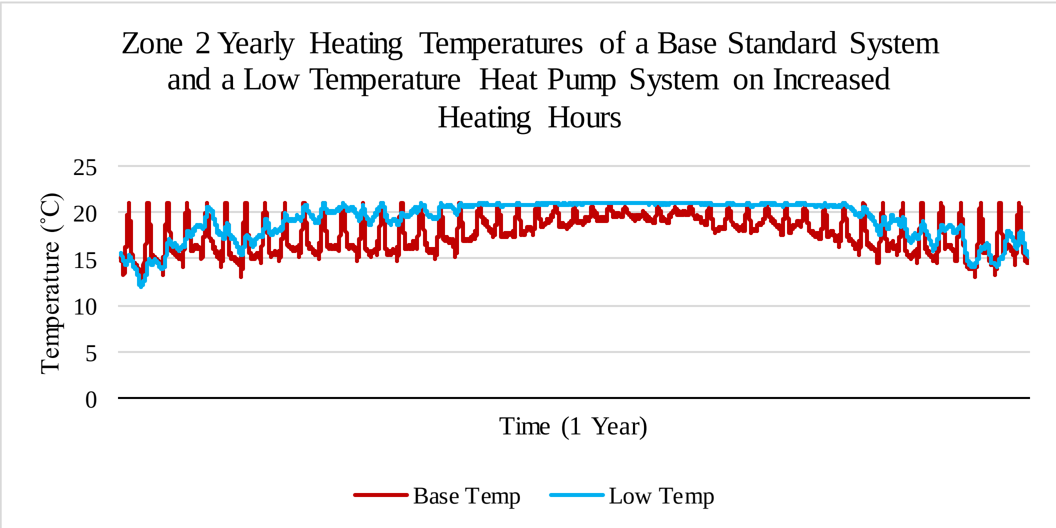
Appendix XI – Zone 2 Results

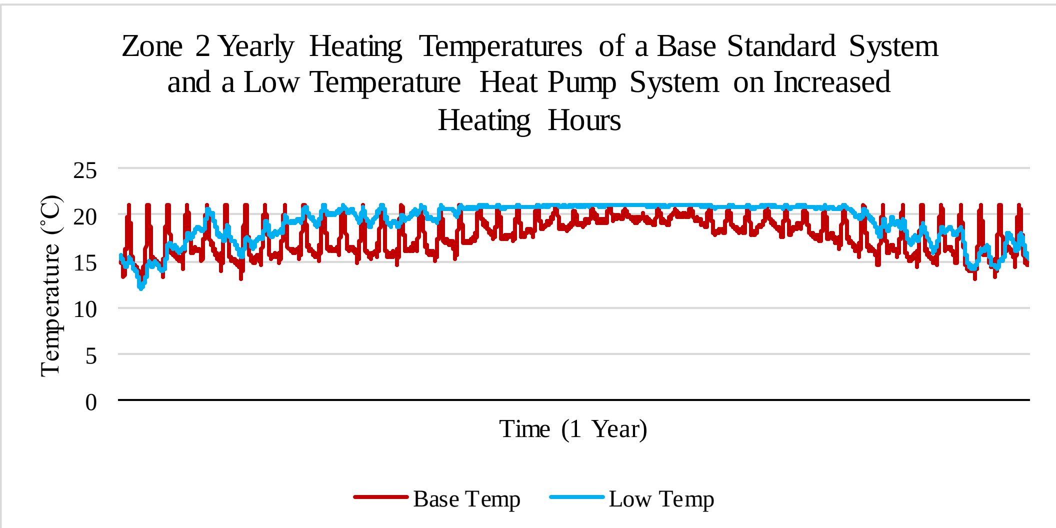







Zone 2 Yearly Heating Temperatures of a Base Standard System and a Low Temperature Heat Pump System with Added Retrofit
Temperature (°C)
25
20
15
10
5
0
Time (1 Year)
Base Temp
Low Temp


Zone 2 Yearly Heating Temperatures of a Base Standard System and a Low Temperature Heat Pump System on Increased Heating Hours
Temperature (°C)
25
20
15
10
5
0
Time (1 Year)
Base Temp
Low Temp


Zone 2 Yearly Heating Temperatures of a Base Standard System and a Low Temperature Heat Pump System on Increased Heating Hours
Temperature (°C)
25
20
15
10
5
0
Time (1 Year)
Base Temp
Low Temp