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DELIVERING DISTRICT ENERGY FOR A NET ZERO SOCIETY

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MSci

Submitted in fulfillment of the requirements of the

Degree of Doctor of Philosophy

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Abstract

District energy systems have been hailed as the cornerstone of any Net Zero carbon energy system, yet there are still distinct operating and design challenges in implementing an efficient and economic system. The novelty of this thesis therefore lies in attempting to providing routes to efficient district energy systems.

Many dwellings will be uneconomical to connect to a heat network without significant investment to improve building fabric. This is demonstrated using dynamic modelling of common UK building stock. Transient System Simulation Tool (TRNSYS) is used to demonstrate the criticality of good building fabric on the potential to reduce operating temperatures in district energy networks, and therefore improve the overall system efficiency. It was shown that improving building conditions alone could offer a 30% reduction in space heating energy consumption, while building improvements and heat pumps could see a 70% reductions

5th generation energy networks are considered. Detailed building energy simulation modelling is given to identify indicative heating and cooling profiles of common building types which are then programmed to a linear optimization to identify the benefits of an energy sharing network. Key performance indicators are identified. This is of increasing importance as network designers begin to grapple with energy sharing network design considerations. The work showed the potential to reduce the levelised cost of energy by 69%, and carbon emissions by 13%. The critical finding however, was that thermal energy storage has the largest impact on energy sharing capability. To further validate the key performance indicator concepts, a more detailed non-linear optimization is given which discusses in greater detail the role of operating temperatures and flowrates on the system design. It was shown that traditional metrics become disconnected from ambient loop networks (e.g. linear demand density).

The overall conclusions of the thesis show that although heat networks have suffered poor performance in the past, there are clear paths to improve this. However, this depends on choosing the correct connections to the network and understanding how to optimize for retrofit demands.

Contents

List of Tables

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List of Publications

The work presented in this thesis has been published in peer-reviewed journals. Publication details are given below.

1. Millar M, Burnside N, Yu Z. District Heating Challenges for the UK. Energies. 2019;12(2):310.

2. Millar M, Burnside N, Yu Z. An Investigation into the Limitations of Low Temperature District Heating on Traditional Tenement Buildings in Scotland. Energies. 2019;12(13):2603.

3. Millar M, Elrick B, Jones G, Yu Z, Burnside N. Roadblocks to Low Temperature District Heating. Energies. 2020;13(22):5893.

4. Millar M, Yu Z, Burnside N, Jones G, Elrick B. Identification of key performance indicators and complimentary load profiles for 5th generation district energy networks. Applied Energy. 2021;291:116672.

Acknowledgements

There are times I look back, and wonder where the time went, and yet there are other days when it seems so long ago I was sitting at a wobbly, booze stained dining table in Wallace street, listening to the cars go past while trying to cram in some procrastination before a shift in Tesco.

Today I'm sitting at a slightly nicer, but no less booze stained, table wondering how to thank all the people who helped me along the way. Here goes…

First of all, there's no project without the supervisors; Dr. Neil Burnside and Prof. Zhibin Yu. You both supported every idea I had, listened to my endless moaning, but most importantly gave me the opportunity to find out what I want to do in life. Well, it's not academia (sorry!) but without your support and the opportunities you provided, I would probably still be stacking shelves.

Ms Heather Lambie. Again, someone else who listened to my endless moaning! More importantly, you kick-started my career outside academia, an opportunity that I am still incredibly grateful for. What started as a six-month placement allowed me to find what I enjoyed about engineering, at a time when I questioned if I should even bother finishing the PhD.

Speaking of that placement, this thesis wouldn't have been completed without the support from colleagues at Hoare Lea. Bruce, Greg, and James; more people who tolerated my endless moaning (there's probably a theme here…). You had the patience to entertain my endless questions, gave me my first professional job, and welcomed me into the team when there was nothing for you to gain from it.

During the PhD, I've been supported to go all over the place; Germany (albeit cut short by Brexit!), Copenhagen, Hong Kong (and then COVID happened), Dubai, London. A huge thank you for all the external funding received to make this happen. How am I going to afford my holidays now?

Family, friends, and loved ones. The years of me trying to explain what a heat network is might not have paid off, but your listening certainly did.

Nathan. “Must be nice to be a student”; can’t say that anymore, can you? You’ve helped me probably more than you know and all I can say is thank you!

Corin (remember that dodgy table?), we started this journey together, we procrastinated a lot along the way (me a lot more than you), and it looks like we’ll be finishing it together. Thanks for always being up for a pint and a moan.

Kane. I’m writing this as you prepare to go off on your own journey (well, technically you’re in the phone shop right now, but you know what I mean) and wondering how I can ever thank you for everything you’ve given me in the last four years. Does it need saying?

The last person I’d like to thank will probably never read this, but I could honestly say that I wouldn’t be where I am today without the encouragement of one high school chemistry teacher; Ms McNally. You helped me at one of the most challenging times of my life and encouraged me to find value in myself. Without you, I wouldn’t have discovered a love of chemistry (and later a hatred for it) that pushed me to go to university in the first place.

Author's Declaration

No portion of the work referred to in this thesis has been submitted in support of an application for another degree or qualification of this or any other university of learning.

1. Introduction

1.1. Project Motivation

Climate change is arguable one of the largest threats this generation will face. As part of this multi-faceted problem, countries across the world have been making commitments to reduce carbon emissions for over 30 years, arguably with very little effect[1]. In the UK, progress has largely been made from replacing coal power stations with gas and offshore wind. This has contributed to the rapid decarbonisation of electricity; but what about heat?

Historically, the UK depended heavily on crude oil from the middle-east to supply domestic properties with oil for space heating. In the 1970s, Arab oil produces imposed an embargo which heavily reduced the supply of oil to the UK, Europe, and the USA. As a result, many countries sought to strengthen their energy security and limit energy dependence on foreign nations. The UK invested heavily in North Sea oil and gas which over time led to the UK's national gas grid. This supplies incredibly low cost natural gas across the UK. For many years since then, houses were built with the intention of being supplied gas from the national grid, rather than oil burners due to the increased safety, low cost, and security.

These benefits are today the root cause of the climate challenges we now face. Natural gas combustion has been estimated to cause 96% of the residential carbon footprint for the UK in 2019 (around 23% of the total UK carbon emissions) [1]. While other countries face similar problems, they approached the oil crisis in different ways. Denmark had very limited access to local oil reserves, so could not self-sustain from internal resources alone. Instead, Denmark focused on improving the efficiency of gas usage to reduce the volume of gas required from foreign countries. This pushed the agenda for mass adoption of Combined Heat and Power (CHP) district heating networks, which had much higher overall efficiency than separate electricity and heat production. Today, over 60% of residential properties in Denmark are connected to a district heating network [2]. In

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[1] Carbon emissions are often used synonymously with climate change, however climate change encompasses much more than just carbon emissions (e.g. warming oceans, melting ice caps, deforestation etc.). However, carbon measurement offers a tangible metric for assessing progress in climate change mitigation, and so it is often used within the energy industry.

contrast, only about 2% of residential properties in the UK are connected to a heat network [3].

The primary motivation of this work has been to explore the reasons why heat networks contribute so little to the UK energy mix, how this can be improved, and exploring the rationale behind heat network expansion in the UK.

1.2. Devolution in the UK

Before progressing the discussion around heat networks in the UK, it is worth clarifying the status of devolution within the United Kingdom.

The UK consists of four nations; Scotland, England, Wales, and Northern Ireland. With the exception of England, each of these nations has its own national, devolved government. The government in England (the UK government) presides over all reserved legislation. This includes all legislation for England, plus any area of legislation which has been specifically reserved from the devolved nations.

When reference is made to “the UK”, this is usually in the geographical context. Great Britain is Scotland, England, and Wales.

The devolved powers to each government is not the same. For example, the Scottish government has powers to create legislation over heat within Scotland, while this same power comes with caveats in Wales.

1.3. District Heating in the UK

Although heat networks have existed in the UK in one form or other since the early days of the industrial revolution, the UK has not been able to replicate the Danish success in this area. Heat networks became regulated very early on in Denmark after the oil crisis, while there is almost no regulation around heat networks in the UK to date. This in effect forces heat network connections into a monopoly market. There is no route for recourse if a heat network operator has poor service (or indeed no service), there is no price cap for heat sales, and heat offtake agreements are usually very difficult to escape (often 20+ year agreement).

Yet, the UK plausibly still has a strong case for making heat networks a success. One crucial benefit of heat networks is the potential to recover low grades of thermal energy at a large scale. Examples of this could be waste heat from industrial processes, water from pumped flooded mine workings, or heat recover from cooling processes (e.g. data centers). It is therefore clear why the Committee on Climate Change (CCC) expects 18% of the UK heat to come from heat networks by 2050 to be able to economically meet carbon targets [4].

This is easier said than done. Outside of London, there are very few examples of successful, large, city wide heat networks but many examples of poor performing networks. In many districts, the local authority requires new developments to detail why a new development is not connecting to a city wide heat network; this is often a planning requirement even when no city wide heat network exists. When a heat network does exist, the planning applicant must give good rationale for not connecting to the network. Very often, the heat network is led from CHP. While CHP may have once been a good carbon saving method, the rapid decarbonisation of electricity in the UK has made gas fired CHP significantly higher in carbon than electricity. Therefore, it is very clear to see how well intentioned carbon saving policies and technologies have crippled the heat network industry across the UK.

1.4. District Heating in Scotland

In Scotland, heat policy is devolved to the Scottish government. This does not give the Scottish government free reign over heat networks, as many other policy areas which overlap with heat networks are still reserved to the UK government (e.g. consumer protection). This prevents the Scottish government taking meaningful steps to regulate the heat network market. Nonetheless, the Scottish government has pressed on with heat network expansion (for better or worse) and has legally committed to meeting 8% of the Scottish heat demand from heat networks by 2030.

Scottish building stock has not historically been developed for heat networks. Like many countries, the built environment within Scotland is heavily routed in the local culture and heritage. In the 19th/20th century, Scotland's industrial economy began to boom. This led to a huge rise in the city populations, and caused a demand for high density housing. The problem was solved through tenement buildings; renowned for the tell-tale sandstone façade. While these tenements weren't designed for district heating, they have many qualities that support district heating (high thermal mass in the building envelope and high demand density). Yet what favorable qualities they have are almost always mitigated through high air permeability (infiltration). The heat lost through infiltration has to be replaced in order to keep the building at a comfortable temperature. This hasn't been an issue in recent years, as gas boilers can comfortably provide high temperature water to radiator circuits. Renewables on the other hand, cannot currently provide high temperature water through non-combustion processes at an affordable cost to users. Therefore, although reasons differ, the resounding message across the UK is the same. Existing buildings have not been designed for district heating.

Legislation has pushed to tighten building constructions. The UK government has proposed that new buildings will have an external wall with maximum conductivity of 0.26 W/m^2K, compared to sandstone which can be as high as 1.5 W/m^2K. Tightening building regulations for new buildings will inevitably address the low temperature supply issue (albeit adding overheating issues), but does not address existing properties [5].

Any solution to this problem should be capable of servicing existing buildings with minimum renovation, should be low (or zero) carbon, and should be minimally disruptive to the end user. Thankfully, some solutions already exist.

1.5. Vapor Compression Heat Pumps

Heat pumps are another type of technology that is not new, but has also never received mass attention in the UK domestic heating sector. By using electricity, heat pumps make use of a vapor compression cycle to upgrade low grade energy to a higher grade energy, with incredibly high efficiency. However, efficiency will never beat cost in the domestic sector. Electricity can cost around 18p/kWh, while gas is currently around 4p/kWh. Assuming heat pumps have a Coefficient of Performance of 3 (discussed in detail below) and gas boilers 90%, the cost of heat from a heat pump is around 35% higher than the current alternative.

The argument for heat pumps is therefore not a cost benefit, but a carbon benefit. Electricity within the UK is expected to decarbonize close to 0 kg CO_2/kWh by 2050, while natural gas is 0.2 kg CO_2/kWh.

1.6. Thesis Aims

In light of the discussion above, there is clear challenges to deploying heat networks within the UK. This work has aimed to understand these challenges in greater detail than previous studies, and critically evaluate the efficacy of widely proposed solutions.

The objectives of this work can be summarized as:

- To identify, discuss, and disseminate the historic, social, political, and economic challenges of heat network deployment within the UK in order to propose mitigation measures and solutions to climate changed caused by heating and hot water systems

- To define the limitations of current market ready solutions for target markets through detailed thermal modelling

- To present tangible learnings for novel 5th generation district energy networks which can facilitate meaningful development conversations between industry, academia, and policy makers

- To dissect traditional heat networks assumptions and metrics within the context of 5th generation district energy sharing networks and understand the contrasting operational strategies of thermal energy sharing networks and non-energy sharing networks.

1.7. Thesis Structure

The thesis presented has been structured as an alternative format thesis. Although the overall thesis presents the work and details which would be expected from a traditionally formatted thesis, there are a number of nuances to be aware of. This section details differences to be aware of, but also outlines how each chapter and publication link together.

Chapter 2 is the first literature review section. This section reviews the state of heat networks in the UK, identifies where mistakes have been made in the past, and begins examining the complexities of the political landscape. This was originally targeted as an introductory paper, giving an entry level understanding to heat network technology and challenges. At the time this paper was written, there was very little published works which could provide a beginner's level understanding of heat networks, which is the gap this paper sought to fill. The paper discusses many of the drivers and pitfalls heat networks have faced in the UK.

When I finished the paper in Chapter 2, I realized that the subtleties of delivering an efficient heat network were much more far reaching than I had anticipated. Heat networks have evolved over the years and solutions have already been proposed to the challenges which I discussed in Chapter 2. These solutions largely take the form of lower temperature district heating networks. These networks offer many energetic benefits, but in practice introduce a host of new issues (e.g. legionella control, larger pipework, increased cost etc.). These issues are well known throughout industrial practice but are again missing from academic sources. Therefore, the paper in Chapter 3 continues the discussion from Chapter 2 but focuses specifically on the challenges created by low temperature district heating networks.

After spending so much time reading about low temperature district heating networks, I started to question the practical implications of these systems. Low temperature heat networks operate at much lower temperatures than localized combustion systems. This presents an obvious question; can low temperature district heating be used to service existing buildings? The work presented in Chapter 4 addresses this question.

When I concluded the work in Chapter 4, I wanted to address two questions that were raised during the work on Chapter 4. The first; how can low temperature heat networks be made to work with existing infrastructure? The second; how can I demonstrate this in a way which is useful and practical for industrial use? The first question was answered by looking to the emerging “5th generation” district heating networks. The second question was addressed by presenting a study which analyses the energetic demands of multiple common building types for suitability in a thermal energy sharing network. This is given as a paper in Chapter 5.

The work in Chapter 5 raised more questions and challenges. By design, the work in Chapter 5 was a linear model which did not account for the dynamic nature of heat networks. Assumptions were made in Chapter 5 in order to simplify the problem such that the outputs would be of use at an early design stage, but clearly needed to be extended upon for detailed design. Chapter 6 therefore gives the final published paper which is a dynamic, non-linear optimization of a thermal energy sharing network. This work shows how temperature and flow variations, coupled with optimal demand placement can alter the dynamics of a thermal energy sharing network.

Finally, Chapter 7 summarises the work as a whole and discusses the findings presented.

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2. Literature Review: District Heating Challenges for the UK

2.1. Introduction

The Paris Agreement sparked a global rush to de-carbonize and keep the increase of global average temperatures below 2 °C beyond pre-industrial (1990) levels, continuing and improving the commitments laid out by the 1997 Kyoto Protocol. While the resultant political and research climate has strongly focused on the de-carbonization of electricity production, thermal energy production accounts for around 50% of energy consumption in Europe, and therefore a significant contribution to carbon emissions [1]. In December 2018 at the 24th Conference to the Parties of the United Nations Framework Convention on Climate Change (COP24), guidelines were laid out to finalize agreements on how to implement the Paris Agreement [2]. In 2017, the UK produced 50.1% of electricity from low carbon sources—leaving another 50% produced primarily from natural gas [3]. These centralized natural gas power plants can be more efficient than traditional coal fired power plants, but do not come close to the possible efficiency and carbon reduction of a well-planned and operated, de-centralized district heating and energy network.

District heating is not a new technology—it has large potential and is fairly well documented—yet it only has an average market share of 10% throughout Europe and is primarily restricted to northern and central nations [1]. This can be related to the 1970s energy crisis, which encouraged many countries to seek and adopt strategies that would make them energy independent, such as significant investment in solar power and energy networks in places like Denmark and the Netherlands. This was not the case in the UK, where a focus on utilization of large coal and natural gas reserves led to an overlooking of alternative low-carbon energy sources, and a comparatively minor transition from oil boilers to readily available, and low cost, coal and natural gas [4].

While it is a centuries-old technology, district heating is only now emerging as a critical player in the challenges of reducing carbon emissions and improving the efficiency of energy use [5]. District heating has been recorded as far back as the 14th century in France, but not recorded until much later in the United States, around the late 19th century. District Heating Network (DHN) classification is commonly based on heat transfer fluid, energy source, energy supply, or time period of installation [6,7]; however, the definitions laid out within these categories are often inconsistent across published examples. To gain any appreciation, the individual scheme should always be considered and not a vague description of “generation”. Figure 2.1 summarizes district heating and energy development. It shows how DHNs have evolved from a very high enthalpy, low technology (1st Generation district heating) into a much lower enthalpy and technologically diverse heat and energy supply (3rd and 4th Generation district heating).

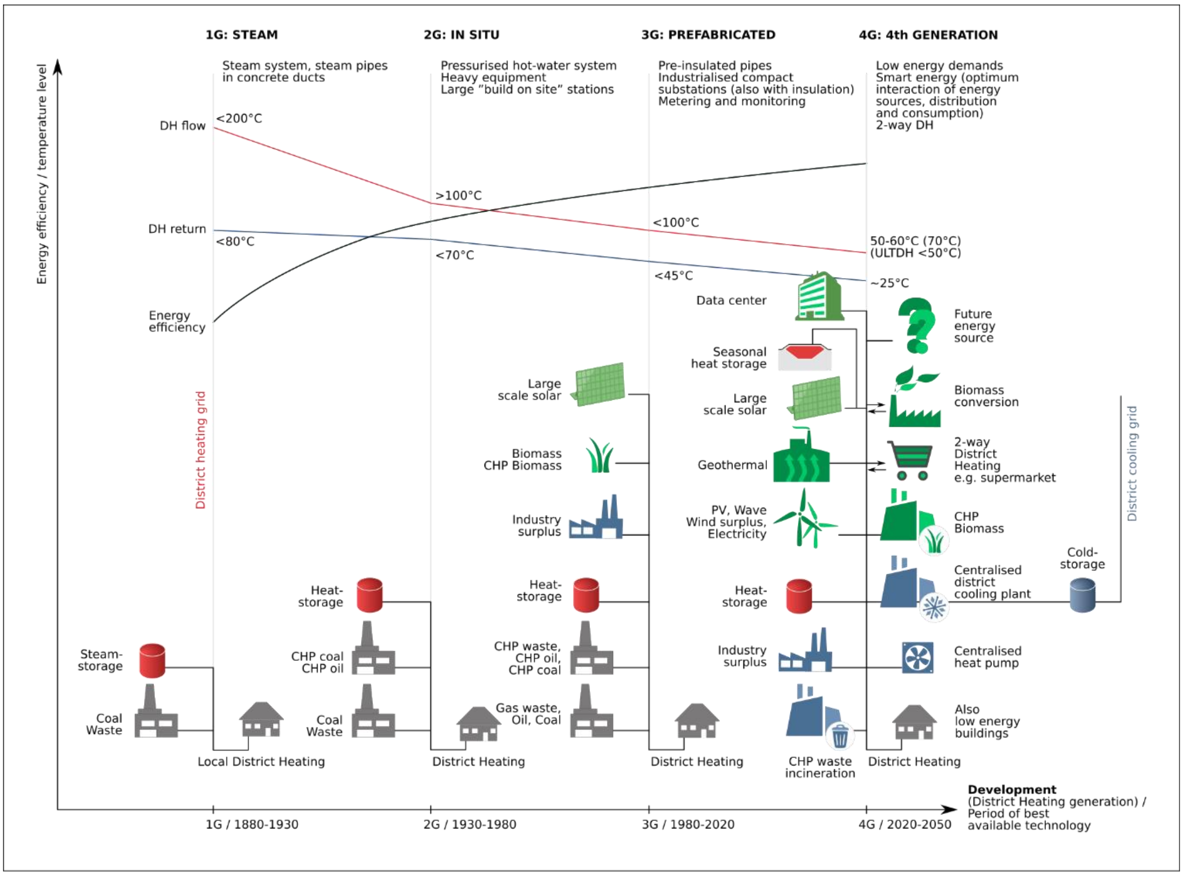


Figure 2-1 Summary of district heating and energy evolution, from 1st to 4th generation [8].

2.1.1. *First Generation (1G) District Heating*

The first generation of district heating was primarily high temperature and pressure steam, delivered through concrete ducts. Note that this is slightly different from the very early transport of hot water from geothermal sources, found in early Roman cities, and different from early steam transport for electricity production.

At the time, steam was a good choice—an extensive water network was not yet developed, steam was readily available from early power plants and could meet the demands from single large users (e.g., hospitals, industrial processes). These schemes could operate at conditions around 300 °C and 20 bar, creating a host of feasibility issues. At such harsh conditions, cast iron piping rapidly corrodes, and without significant insulation, any water coming into contact with the outer surface would vaporize. Any steam condensation on the inner pipe would result in high pressure water within the distribution system, damaging pipework through cavitation and higher corrosion rate. In addition, such high temperature fluid has a significant energy loss in the distribution system, lowering the efficiency of any such scheme. In modern day district heating, these schemes have high operating and maintenance costs, are difficult to connect to end users (high/low pressure interface) and have high thermal losses.

Few 1st generation schemes still exist, however one of the largest can still be found in Paris. This scheme is operated by the Parisian Urban Heating Company, and delivers steam (predominantly sourced from waste incineration) along 480km and cooling along 71 km of pipeline. This is a good example of the fluid definitions often associated with district energy—this delivers steam similar to a 1G scheme, but combines heating, cooling and power with thermal storage like a 4G system, with low temperature loops, like a 3G system (described in Section 1.3 and 1.4).

2.1.2. Second Generation (2G) District Heating

Second generation (2G) district heating began to emerge in the early 20th century. The opportunity to improve district heating schemes came to much of Europe as a result of re-construction work post World War 2, explaining why cities like Berlin and Bucharest have extensive networks [4]. The newer schemes operated at higher temperatures (>100 °C) and higher pressures than before, transporting super-heated water [9]. These systems primarily worked on two pipe closed loop systems (one supply pipe and one return pipe, similar to 1G, shown in Figure 2.2), meaning the returning condensate could be re-used or matched with a lower grade heat demand. The fluid was easier to manage, as significant improvements in hydraulic pumps had been made, allowing pumping stations to transport fluid across much further distances than before in 1G systems, with the entire pressure head met by one pump at the source. This, combined with improved piping and insulation, meant that the overall efficiency improved dramatically, encouraging many European cities to adopt district heating schemes as modes of primary heating and not just in the areas of highest population density.

At this time, Combined Heat and Power (CHP) was also growing in popularity, creating the possibility to tie exhaust gas heat with the district heating schemes. So while direct fossil fuel burners (coal and oil) were still the leading source of energy to the schemes, CHP was now being used to produce local electricity as well, reducing the cost of electricity and pollution in cities [6].

The improvements made have been suggested to increase efficiency from 1G to 2G by around 50%, however there was still much to be desired from 2G systems [10,11]. These systems often had painfully high capital costs, requiring thermal storage tanks and shell and tube heat exchangers at many end users, which, in conjunction with the high thermal loss and lack of system control, necessitated the development of 3rd generation district heating schemes.

2.1.3. Third Generation (3G) District Heating

Third generation (3G) district heating is currently the most popular version, and most new schemes follow this template, with 3G district heating becoming popular in the 1970s and 80s [4,6,9] alongside significant improvements to manufacturing processes. This newer form of district heating was brought on by increasing oil prices, generating incentive to produce more efficient and lower cost energy systems. These systems use high pressure water (similar to 2G), but at temperatures below 100 °C. A typical 3G transmission and distribution network will consist of much more compact materials. Pipes are thinner than 2G and pre-fabricated, usually with significant thermal insulation and placed in the ground. Shell and tube heat exchangers were replaced by plate heat exchangers, offering a more compact footprint and the ability to extend networks by the addition of plates to the heat exchanger. The change in heat exchanger also lowered maintenance and down-time due to the ease of cleaning and maintenance [12]. These changes lowered the cost of new systems, allowing many developments in countries that had previously been resistant (such as the United Kingdom). In this time, natural gas prices were low, encouraging larger CHP to dominate district heating supplies. Heat Interface Units (HIUs) started to appear in a more developed way in 3G district heating, allowing individual temperature control, rather than merely a pressure/temperature interface from the network to the end user.

There are many examples of 3G district heating, such as the Athletes Village in Glasgow. This district heating scheme was designed for the 2014 Commonwealth Games athletes' accommodation, and post-event, redevelopment into residential housing, and includes a 28 km network, providing heat to over 700 homes, large sports facilities, a care home and community buildings. The network is fed by a 1.68 MW CHP engine, operated at 85 °C and return at 60 °C. Each user as an HIU, essentially two plate heat exchangers (one for space heating, one for domestic hot water) with pressure control valves and auxiliary equipment. This allows the network to operate at any chosen temperature and pressure, without major concern for end user systems.

2.1.4. Fourth Generation (4G) District Heating

In all previous generations, there has been a lack of focus, incentive, technical ability or manufacturing capability to improve heating systems past basic and fairly rudimental enhancements. These factors can now be significantly improved and have a strong potential to produce well integrated heat and energy systems—smart fourth generation district heating, cooling and power. Lund, Werner, Wiltshire, Svendsen, Thorsen, Hvelplund and Mathiesen [10] identify key issues surrounding 4G district heating including integration with the transport sector, incompatibility with current infrastructure, space heating requirements and low heat demand density. However, 4G DHNs attempt to solve these problems by better sourcing and matching energy sources with user demand. This includes operating at lower temperatures than 3G (e.g., 60/40 °C), incorporating a larger share of low carbon energy sources and supply/demand management.

One of the largest efficiency losses from district heating is from secondary factors associated with end users. This is a difficult issue to address because it is caused by low quality buildings, high network supply temperatures and poor end user management. The current building stock is built to comply with current legislation (Buildings (Scotland) Act 2003 and Climate Change (Scotland) Act 2009), which does not plan for a sustainable future or any future district energy integration [13,14]. Figure 2.2 shows the number of demolished properties in Scotland compared with the number of completed new build homes and the total number of homes [15-17]. This shows that, while a significant number of new properties are entering the market, very few are being removed. This means that older properties will have a significant impact on future energy efficiency and must be considered now, not in the distant future when political concern is more likely to be directed at the heating sector.

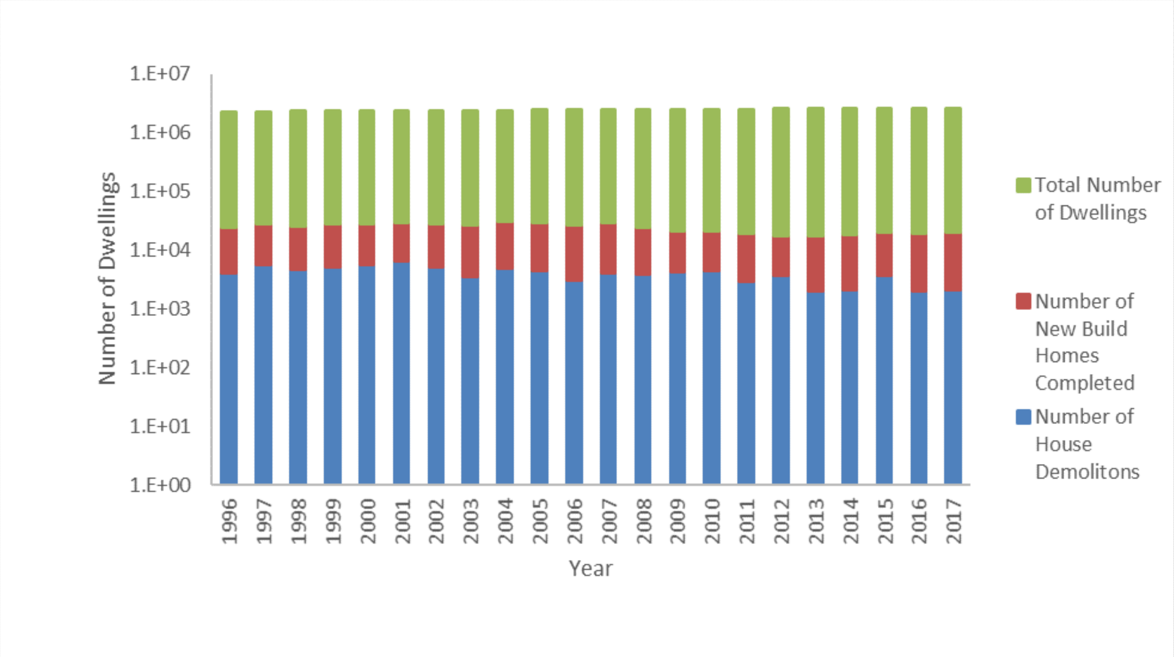


Figure 2-2 Chart of Scottish dwellings built, demolished and total for Scotland between 1996 and 2017 [15-17].

A number of studies have demonstrated that older building stock can be upgraded and integrated with lower temperature district heating networks to allow for operation at supply temperature of 45 °C for space heating [10,18-21]. It has been shown that reducing the operating temperature of DHNs from 80/40 °C (typical of 3G DHN) to 60/30 °C can provide over 30% saving of heat losses from the network [18]. It has been proposed that to operate at lower supply/return temperatures will require upgraded infrastructure, including improved radiators with return temperature thermostats and control, improved control systems and significant energy renovations, such as wall insulation and double glazing [22].

A critical part of 4G DHNs is the integration of low enthalpy heat sources, such as excess industrial heat. It has been estimated that the EU has over 300 TWh/year of waste heat potential, with almost 30 TWh/year from the United Kingdom alone [23]. This should be seriously considered as a heat source when planning a new DHN, however it is likely to be difficult in the UK due to the necessary and complicated balance between the agreement with the industry source, the DHN operator and maintaining a competitive cost to the end user.

2.2. Energy Supply

There are several thermal resources commonly utilized for DH systems. The following sections discuss each of these individually in detail, but it should be noted that DHNs are often fed by multiple sources in an integrated fashion. Examples of this could be a CHP system, with a heat pump to upgrade heat captured by a cooling jacket and thermal storage, or a geothermal borehole, with heat pump for heat abstraction and storage combined with a solar collector. The energy source will primarily depend on the end use and requirements. End use typically falls into one—or a combination—of the following:

- Space heating
- Domestic Hot Water (DHW)
- Industrial process

The energy supply can range from a few kW to large MW scales, and not all sources are suited or scalable across the entirety of this range.

2.2.1. Combined Heating and Power (CHP)

CHP (a form of co-generation) is an electrical power producing engine, usually a gas turbine or micro gas turbine, which produces power locally to the user, and can therefore capture the high grade heat from combustion-produced flue gases. CHP schemes have been installed in hundreds of district heating schemes around the world due to their profitability [24-27]. Heat is recovered from the highest temperature source, the exhaust gases (circa 400–500 °C), but can also be recovered from lower grade heat from the cooling jacket or lubricating oils (<100 °C). CHP can range from a few hundred kW_e to several MW_e.

Early publications on CHP date from the 1970 and 1980s and primarily focus on proving a case for CHP installation [28-33] in order to offer an early strategic, operational and economic basis to develop co-generation systems. In the 1980s, significant investment and changes in policy allowed for further development, particularly in Denmark and Holland [34,35]. Some of this work began to computationally investigate thermal losses from the network [36] and assess the commercial viability of CHP DHN schemes in the United Kingdom [37]. By the 1990s, published works had a far greater technical focus, including one of the first linear optimizations of DH [38], which considered the costs of electricity and heating at different times across the year and suggested an operating schedule to minimize the operating costs. This method is still used today and features in many recent publications [39-41]; however, it is almost exclusively focused on a cost optimization and has little consideration for operational constraints or targets, such as carbon emissions. By the 1990s, carbon emissions were being acknowledged as a significant concern, and yet even now, CHP operating strategies rarely target carbon footprint minimization, so continued use of this methodology demonstrates a persistent disconnect between political and environmental motivations and technical advancements. This may be because with much lower penetration of renewables into the national grid at the time, CHP could offer a significant carbon reduction at the time and was one of the few commercially viable systems. That is no longer the case in the United Kingdom, and as the share of renewables increases, the viability of fossil fuel CHP dwindles. For CHP to have a sustainable outlook, it must adopt routes to reduce carbon emissions—potentially through biogas combustion or waste incineration.

Biogas combustion for co-generation has been considered in the past [25,42-45], but availability, transportation and mechanical constraints have prevented it replacing natural gas CHP. Biogas is a strong solution to a critical problem for CHP, as it incorporates a renewable fuel source into co-generation and reduces waste [46,47]. Most CHP schemes will have a finance plan across 20–30 years, meaning this “dirty” energy production is unlikely to shift without incentive. Although biogas conversion is not a perfect solution and cannot be applied to all engine types, it does offer some promise as a long term, low-carbon CHP fuel source.

2.2.2. Heat Pumps

Heat pump technology can be applied to a huge range of heat sources. They are commonly found in conjunction with CHP technology and ground source heat extraction.

We primarily discuss heat pumps as a stand-alone technology in the present study, where heat can be readily and easily extracted. However, for optimal DHN utilization, we would typically recommend this technology as part of a wider integrated network.

Heat pumps take a low grade, low value heat source, and with a small amount of work energy, convert it to a higher grade, higher value heat source. The technical details of this process are not discussed here, but are well documented elsewhere [48-50]. There are two heat sources which are widely used and well suited to heat pump technology—air source and surface water source heat pumps. Air (e.g., data centers [51-54] and ambient air) and water (e.g., river water, sewage water [55-59] or sea water [60-64]) are largely available and a free resource, making good candidates for heat pump applications. Data centers can also be used as a heat source. Water is the preferred choice for a few reasons

- Water has a larger density than air, and therefore greater volumetric energy density
- Water temperatures are relatively constant and predictable across the year, where air can vary drastically diurnally
- Air source heat pumps require loud blowers and create more noise

River water is a huge thermal reservoir of un-tapped potential. There are very few river source heat pumps in operation, which could be due to the difficulty in matching thermal demand and network infrastructure or the necessity to take potentially variable natural parameters into consideration. Further problems can be caused due to the harsh conditions found in river water. Qin, et al. [65] show that fouling of the heat exchangers caused by river bacteria and algae can reduce the Coefficient of Performance (COP) by 3.73%, and suggests that a maximum performance is when the sediment concentration is below 100 g m^{-3} and turbidity below 50 NTU [66]. However, this paper did not consider direct heat transfer from the river to the heat pump, only experimental simulation of river conditions. No discussion is given around heat exchanger choice or pre-treatment to minimize the fouling effect, leaving much work needed before practical and reliable guidelines can be suggested. However, this work is significant, as it is among the first research to begin questioning the operability of river source heat pumps.

Drammen, in Norway, is home to a significant DHN dating back to 2002, including 13 MW_T of sea-source heat pumps. These heat pumps operate at a COP of around 3 year-round, using ammonia as a refrigerant. The network has a summer mode and a winter mode. In the summer, the heating load is significantly reduced from 45 MW_T peak to less than 2 MW_T. In this case, the operating temperature is around 75 °C compared to 120 °C in the winter. This is a mix of both 2G and 3G operating strategies. The system has been shown to save over £1 million and 12,733 tCO_{2e} per year [67]. Although this type of heat pump has been shown to have great potential, it can only be deployed under specific conditions and areas close to suitable bodies of water, so is therefore not suitable for many users.

2.2.3. Geothermal and Ground-Source Energy

The types of heat extraction from the earth are not well defined. For the purpose of this section, we describe ground-source heat as any heat being taken from the ground, subsurface as shallow heat abstraction (typically from horizontal loop heat exchangers) and geothermal from deeper heat abstraction (typically borehole or aquifer).

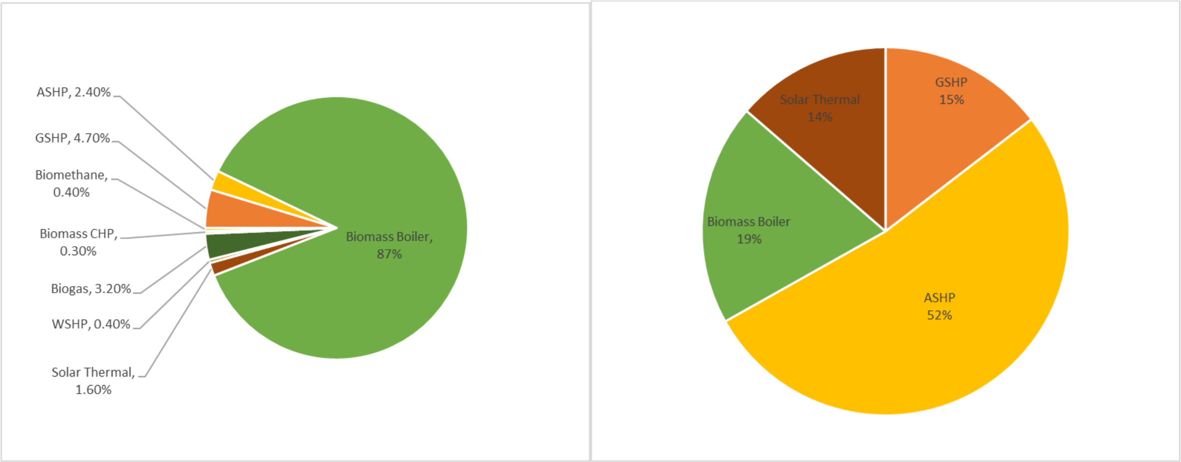
Ground-source heat abstraction is growing in popularity, and since 2010, the number of geothermal and subsurface installations have increased by approximately 20–30% [68,69]. Geothermal and subsurface heat abstraction involves taking heat from the ground, either directly or (usually) in combination with a heat pump. Subsurface energy extraction is predominantly from horizontal loop soil systems at around 1–2 m depth, while geothermal can be from tens of meters to several kilometers, but is usually 40–150 m [70,71]. These systems both extract heat from the ground but with different approaches and prospects. Taking heat from the ground can be traced back to early roman times, however did not begin to become commercially available until the early 1900s [70,72]. Ground source heat is a reliable source of energy, as due to the low thermal conductivity of sediments and rocks, the ground temperature is almost constant throughout the year [73,74].

Geothermal heat comes primarily from radioactive decay in the ground and heat transfer from the hot inner core, either to rock or underground water [70,72]. The core is estimated at 3000–5000 °C at about 6000 km depth, however extraction usually occurs at less than a hundred meters and far below 50 °C [75,76]. The arrangement of geothermal heat abstraction can be open loop but is most commonly a double closed loop system, where the heat pump refrigerant and the ground do not come into direct contact. Instead, heat is exchanged via an intermediate heat exchanger [76]. The various configurations are discussed extensively elsewhere [68,69,77-82]. The most common type of extraction is borehole extraction, where a polyethylene U-tube is placed into the ground and used to pass heat between the ground and a heat transfer fluid. The heat is then upgraded using a heat pump and transferred into the network.

Geothermal heat has been estimated to yield between 50–100 W/m borehole depth of heat pump heating capacity, dependent on ground conditions [70,83]. Anything other than small district heating systems require heat on a MW scale, which would not be economical to extract from a single borehole. For larger heating demands, multiple boreholes are drilled and can have several thousand boreholes, with a capacity of several GW (e.g., Ball State University) [74,84,85].

2.2.4. Biomass and Biogas

Biomass exploitation uses biological solid (e.g., crops, wood and animal manure), liquid (e.g., oils and fats) and gas (e.g., anaerobic digestion or pyrolysis) byproducts. These materials can be burned to produce either heat or electricity. Bioenergy and waste usage has increased in recent years, from 4.1% of UK primary energy consumption in 2012, to 8.3% in 2017 [86]. This increase can be partially attributed to the Renewable Heat Incentive (RHI), which launched in the United Kingdom in 2014, offering subsidy for biomass usage. Figure 2.3 shows the domestic and non-domestic split of renewable energy sources, which are signed to an RHI agreement at the end of October 2018. There is a significant difference in RHI uptake of solid biomass for domestic (19% or 64,642) and non-domestic (87% or > 18,200), including DHS systems [87,88]. This is likely because of the significant cost to individual users, the need to source biomass, a flue exhaust, storage space of fuel (typically 20m^3 for an average dwelling), additional delivery and unloading time, low market choice of fuel supplier and high comparable operating costs to alternatives [89]. District heating offers the benefits of biomass combustion to a wider range of customers, without the end user having to deal with the management of the boiler.



(a) (b)

Figure 2-3 Comparison of Renewable Heat Incentive installations by technology type as of October 2018. (a) Non-Domestic RHI and (b) Domestic RHI [87,88].

Figure 2.4 shows the split of biofuels in the United Kingdom between bioliquids (primarily fats and oils), gas (from pyrolysis or anaerobic digestion) or solid biomass (crops, wood chips, wood pellets, etc.). This shows a significant solid biomass dominated biofuel usage, which can be accredited to the large usage shown in Figure 2.3.

Biomass combustion is often considered a greener alternative to fossil fuels (wood chip—0.015 kg CO_{2e}/kWh compared to 0.204 kg CO_{2e}/kWh natural gas), however many papers have commented on the increase in particulate matter (PM) around biomass burners [90-92]. Although biomass combustion may have a local increase in PM pollution, this is unlikely to significantly contribute to pollution in the United Kingdom.

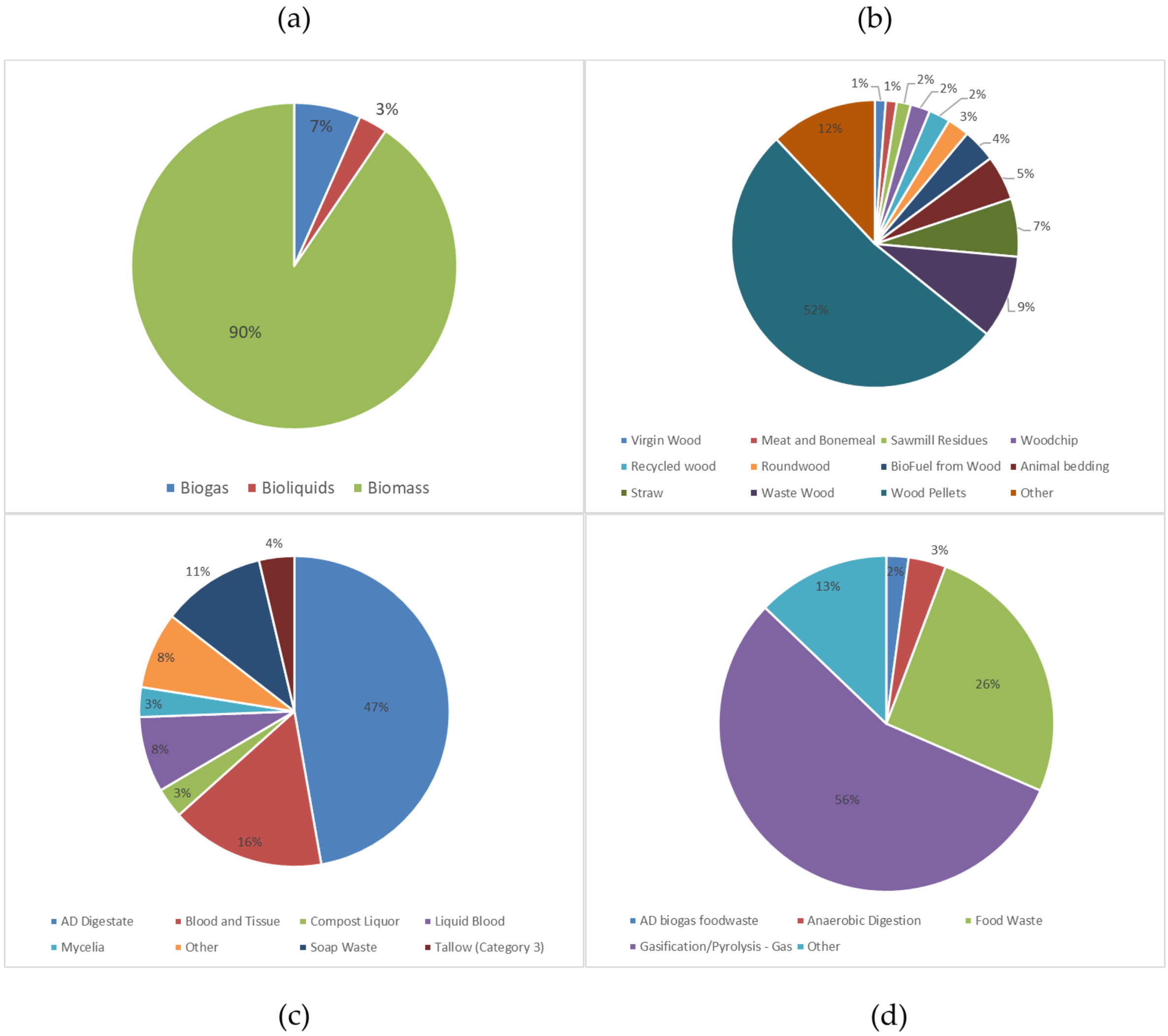


Figure 2-4 UK biofuel usage split for 2016 and 2017. (a) Total split of biofuel usage, (b) split of biomass fuel usage, (c) split of bioliquids fuel usage and (d) split of biogas fuel usage. [93].

A biomass DHN operates much the same as any other DHN, with the exception of the need to transport solid fuel from storage to the boiler, known as the feeding and handling system, described in Table 1.

Table 2.1 Description of Different Biomass Feeding Systems [94-97].

Type of Feeder	Suited Biomass	Space Utilized vs size of biomass (%)	Advantages	Disadvantages
Belt	Pellets Woodchips	20–25	Reliable Simple Low cost Good over large distance	Large footprint required
Screw	Pellets Wood chips Sawdust	45%	No dust emissions Low cost	Easily jammed High power draw
Hydraulic Walking Floor	Straw Cereals	90%	Can deal with non-homogeneous particle sizes	Large footprint
Pneumatic	Pellets Wood chips	N/A	Long distance transport	Low capacity High maintenance Dust leakage

The first community owned biomass district heating scheme in Scotland is the St Bride's Community Centre (55.942645, -3.220485). This is a small scheme, providing 150 kW of biomass heat to the community centre, local church and bowling club from a 50 kW and a 100 kW wood chip boiler. This is fed from a 4-meter agitator and screw feeder and coupled with a 5000-liter thermal store. The feeder can be adjusted to operate from 30% to 100% maximum output, allowing the system to modulate during demand fluctuations. This system replaces oil burners and is expected to save 4849 tons of CO_{2e} per year. The system cost £161,170 and was funded mostly from local grants. It is expected to return around £16, 500 pa from the RHI, and the return on investment is expected to be around 5–7 years [98,99]. This is a small system, operating on a non-profit basis, similar to many schemes in Europe. This allows the system to remain competitive to alternative heating sources and encourages local ownership, improving local opinions and perceptions [98].

2.2.5. Thermal Storage

Thermal energy supply and demand will suffer from large losses in efficiency when the method of heat production must be either quickly increased or decreased. This can occur when a component in the system fails, or more likely, when there is a significant deviation in thermal demand from the anticipated thermal demand. When this happens, the control system can either increase the supply quickly, switch on supplemental gas boilers or use heat from a thermal store. Thermal energy storage (TES) provides a way to shift heat production away from peak demand times and higher cost periods, leading to reduced peak loading, lower heating costs and less mechanical wear on equipment [100].

TES is typically sensible or latent (also called phase change). Sensible TES is by far the most common. Sensible heat storage stores heat in a material by raising the materials temperature, without a phase change. The amount of heat that can be stored per kg depends on the heat capacity of the material and the phase change temperature (either melting or boiling). Latent heat storage forces a material to undergo a phase change, either by adding or removing heat. This will either store or release latent heat. A summary of properties is given in Table 2.

Table 2.2 Properties of Different Thermal Energy Storages (TES).

TES Type	Sub-type	Heat Capacity [70,101]	Energy Capacity [102,103]	Cost (£) [104,105]	Advantages [70,100-102]	Disadvantages [24,70,100,102,103,106]
Sensible	Water Tank	4.18 $\text{MJ}\cdot\text{m}^{-3}\cdot\text{K}^{-1}$	60–80 kWh/m^3	£26–183/kWh	Easy installation Well understood technology Can be single user or district scale	Expensive for small users Only diurnal storage feasible
	Borehole Aquifer	1–4 $\text{MJ}\cdot\text{m}^{-3}\cdot\text{K}^{-1}$ 4.18 $\text{MJ}\cdot\text{m}^{-3}\cdot\text{K}^{-1}$	15–30 kWh/m^3 30–40 kWh/m^3	~ £0.3–3/kWh £600–800/kW	BTES -- Efficiency increases over time Seasonal storage	High capital Low energy density Site specific geological conditions BTES—Low thermal efficiency
Latent	Organic Inorganic Salts Metal Alloys		40–140 kWh/m^3 70–330 kWh/m^3 80–195 kWh/m^3	£40–350/kWh	High volumetric energy density	Low thermal conductivity Low commercial availability Can be incredibly expensive compared to other TES

TES has been shown to reduce overall primary energy usage by as much as 10% [107]. This is due to heat load variation which can be minimized by the use of TES, shown in Figure 2.5.

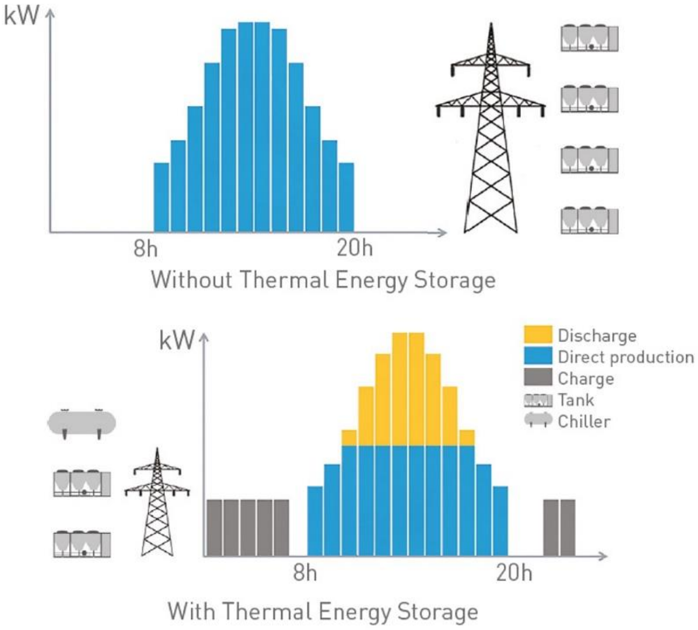


Figure 2-5 Diagrammatic example of thermal dispatch with thermal storage, reproduced with permission of The Carbon Trust [108].

District heating schemes have inherent thermal storage in the network pipes, however this is rarely enough to shave the peak demand [109,110]. This can be utilized by slightly increasing the supply temperature in the network prior to expected peaks, providing a few hours of storage[111]. Large tanks and pit storage can provide daily or weekly storage, while borehole and aquifer storage can provide seasonal storage. The aim of seasonal storage is to provide enough energy to allow the energy supplies to operate at a lower capacity through the heating season, rather than reducing diurnal peaks.

Current research has focused on optimizing supply and demand in networks. Schmidt, *et al.* [112] describes the design considerations for large scale aquifer and pit thermal storage. It is suggested that for aquifer storage, the heating and cooling load should exceed 250 kW, and the economy of scale in storage systems is shown.

While TES has been an integrated part of heating systems in many European countries for years, the uptake in the United Kingdom has been much slower. The current infrastructure in the United Kingdom has been built on a high carbon, chemical thermal storage in the form of natural gas, rather than sensible or latent storage. Currently, the only widely available TES is in the form of Economy 7 tariffs, tied with electrical storage heaters. This charges customers based on a day rate and night rate, charging the store during the night and discharging during the day. For TES to further penetrate the sector, it must support competitive pricing in renewable energy. This is difficult to achieve for small domestic users due to the high cost of small TES, low consumer uptake and consumer tariff control [113].

There are very few documented examples of TES in the United Kingdom. One example is Plockton High school. This is a high school on the North West coast of Scotland (57.334340, -5.666381), with boarding for students. It uses a 400 kW baseload biomass boiler, supplemental oil boiler and three 10 m^3 TES tanks. The capital cost of this project was £624,000 and is expected to save £64,000 per year on energy costs. The distribution network operates at 90 °C, typical for a 3G DHN. This is a fairly small scheme, with a peak load of 590 kW, designed for fuel security in an area of the United Kingdom not connected to the gas grid. The school is able to store around 3 weeks of biomass, providing fuel security the previous oil burner system could not. The thermal profile is given in Figure 2.6. This shows the biomass boiler running constantly at full capacity, loading the thermal store at low demand periods and discharging when needed [108].

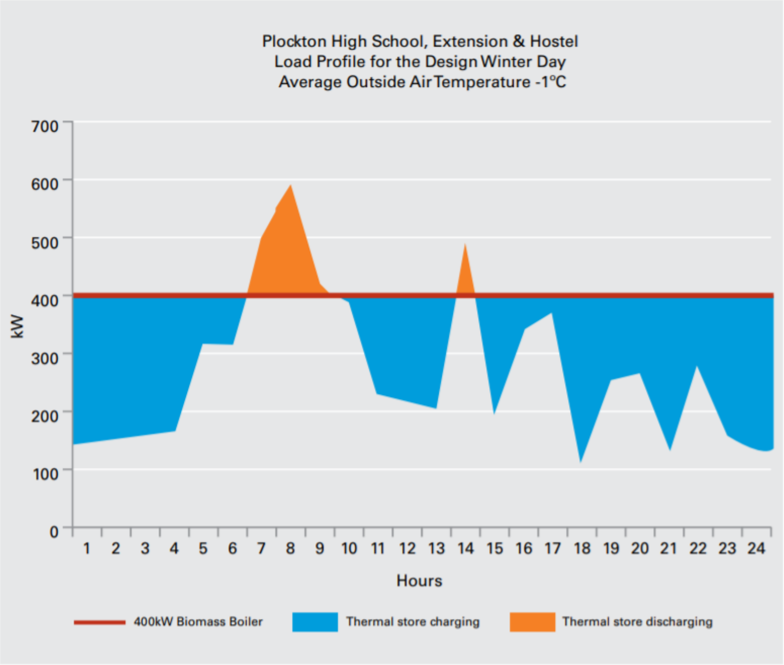


Figure 2-6 Load profile of Plockton High school, reproduced with permission of The Carbon Trust [108].

2.2.6. Load Prediction

District heating can only be deployed successfully when the consumer prices are competitive with alternative heating costs. To achieve this, DHN operators must keep distribution costs as low as possible, and it has been suggested that this will necessitate the use of co-generation, waste incineration, waste industrial heat, geothermal, biomass or a mix of these options [114]. Heating demand is controlled by the end user, while the energy supply center can be several miles away and must respond to demand very quickly. In a perfect case, the heating supply will perfectly match the heating demand. By closely matching supply and demand, the network will run at greater efficiency, leading to lower operating temperatures, lower distribution and transmission costs, which will in turn lead to lower end user costs, and therefore more users connecting to the network, further reducing costs [115-124]. To meet demand, DHN operators can control fluid flow in the network, differential pressure and supply temperature [118]. In many cases, the operator will slightly increase the supply temperature prior to an expected demand spike, slowly increasing heat and storing it for a few hours in the network. To reach any significant improvement in thermal dispatch, a smarter approach to demand management must be adopted.

Artificial Neural Network (ANN) models are a method of short term thermal load prediction, typically a few days or hours [118,125-128]. ANNs are an adaptive learning model capable of processing multiple streams of data in parallel and learning from a dynamic input-output response [129]. The model is presented with example data and known outputs. For a heating network, this could be example temperature or flow adjustments in a distribution system to match a known thermal demand. The model will then adjust the internal connection weights to reduce deviation from the simulated output and target output [130]. The initial learning can require a large amount of data, which isn’t always available from DHSs, however the difficulty in gathering initial data is a worthwhile endeavor, as the ANN can be generalized and applied to other systems once learning has taken place [129,130]. ANN forecasting offers improvement on statistical methods (e.g., time series and regression), as ANNs can provide a non-linear response to a non-linear problem, while statistical modelling is typically linear [131].

Neto and Fiorelli [132] compare an EnergyPlus forecast and a feed-forward style neural network forecast. A feed-forward network has each neuron connected only to a neuron in the next or previous layer. EnergyPlus uses physical constants to model energy demand; further details can be found in the EnergyPlus Engineering Reference document [93]. EnergyPlus struggles to account for human variability. For example, it cannot account for a building occupant randomly opening a window. ANNs are trained from real data, including these random events, and can therefore produce a model capable of incorporating random variables. The results of this study showed EnergyPlus with an error of ±13% for 80% of the tested data, while the ANN model showed 10% error when the forecast is split into working days and weekends [132]. Although the ANN results can be improved, serious improvement must be made before ANN becomes the next widely used energy forecasting tool. These improvements can be made through intensive focus on network training and data acquisition.

2.2.7. Economics and Regulation

It has already been described that DHNs have a low penetration in the U.K. heating market, with the Department of Energy and Climate Change (DECC, which was later replaced by the Department of Business, Energy and Industrial Strategy) estimating there are around 2000 schemes in the United Kingdom, with 55% of these in London [133].

Figure 2.7 shows the fuel type by size of DHN for available data (710 schemes), excluding any unknown fuel sources (1095 schemes). The DECC report defines users as [134]:

- Large—> 500 residential properties or > 10 non-domestic users
- Medium—100–500 residential properties or 3 - 10 non-domestic users
- Small—< 100 residential properties or < 3 non-domestic users

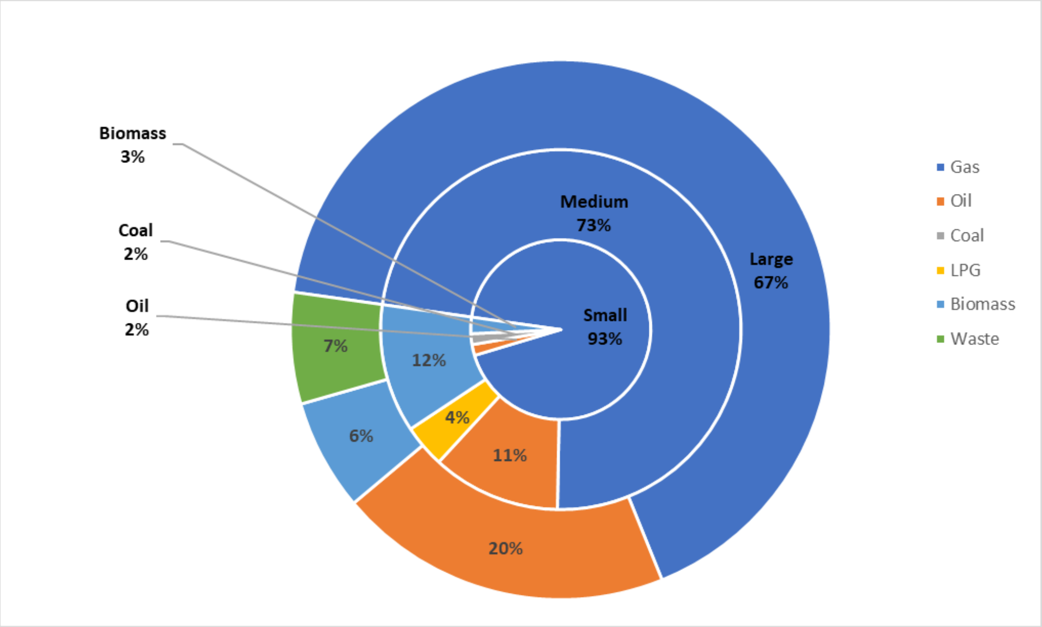


Figure 2-7 District Heating Fuel Type in the United Kingdom by Network Size.

It is no surprise that natural gas is the largest fuel source shown, with the UK gas network estimated to cover 85% of domestic heating [3]. This makes it difficult for new district energy suppliers to get a foothold in the existing gas and electricity monopoly, however it has been shown that once installed, DHNs have a tendency to grow and expand [135]. DHNs in the United Kingdom are typically led by the local authority or by the property developer (however, some community owned schemes are also present). In 2013, a U.K. government funded report identified the key issues to authority led DHN deployment as being financing, while for property developer led DHNs, the biggest roadblocks come from identifying suitably qualified consultants and agreeing financing terms with the service provider [135]. Costs can be significant and stretch beyond simply capital and operating costs—technical and financial viability studies (sometime £60,000), upskilling staff, legal advice and procurement, to name just a few. This creates a significant barrier, which many developers and local authorities would not be able to overcome without significant government help. Since this study was published, the Low

Carbon Infrastructure Transition Programme (LCITP) has been launched in Scotland to support low-carbon projects across. Support available can include project development, expert advice and financial support to those able to provide at least 50% of the initial funding. Example projects supported include the Queens Quay and Clydebank district heating network (£6 million), the Dundee Low Carbon District Energy Hub (£2.9 million) and Callander Local Energy Opportunity (£100,000) [136,137]. This shows a significant government investment and a welcome focus, which has been echoed in Westminster by the launch of the Heat Network Investment Project (HNIP). The RHI is based on the volume of heat produced and the eligible technology. This can be used to support operational costs. For example, a 400 kW biomass boiler might expect an RHI, shown in Table 3.

Table 2.3 Example RHI calculation for Medium Biomass tariffs for systems installed after May 22, 2018. Note that in practice, operation would likely be far < 8,760 h pa, and therefore so would the payment.

Heat generation	Heat Generated per Tariff (kWh)	Tariff (p/kWh)	RHI / year (£)
Tier 1	3066 hours x capacity = 3066 × 400 kW = 1,226,400 kWh	3.05	37,405
Tier 2	Total capacity (400 kW × 8760 hours/year = 3,504,000) − Tier 1 heat (1,226,400) = 2,277,600 kWh	2.14	48,740
		Total	86,145

A significant hurdle to financial viability in domestic schemes is the consumer uptake. Energy Services Providers (ESPs) will have a minimum dwelling uptake to be able to consider a DHN, some will require as many as 500 dwellings to consider a CHP scheme economically viable [135].

As of December 2018, there is no regulator for heating networks, as there is for electric and gas networks (Ofgem), meaning consumers on DHNs have less security than traditional gas and electric consumers. This means there is no ombudsman to receive complaints, which can discourage consumers connecting to the heating network, making it even harder for network owners to make the necessary connections for an ESP to begin talks. The only current legislation specific to DHNs is the Heat Network (Metering and Billing) Regulations 2014, which describes the billing and metering for DHNs but does not legislate the quality of heat, market competition or DHN monopolies [138]. The Heat Trust is a voluntary standard launched by industry participants, while the Association for Decentralised Energy (ADE) and Chartered Institution of Building Services Engineers (CIBSE) have produced a heat network code of practice. Both of these are voluntary, and it is unclear how many DHNs in the United Kingdom meet these standards and practices. Therefore, it is clear that the UK must push legislation and regulation around heating networks in order to provide safe, secure and competitive heating network markets in order to facilitate the 17% predicted domestic heat supply by DHNs by 2050.

2.3. Conclusions

District heating networks have a long and proven track record in EU and the Nordic countries, but have struggled to make headway in the U.K. energy market. Past technology and political climates encouraged alternative heating, and it is only in recent years that the focus has returned to district heating schemes in the United Kingdom and become a part of the government's energy and environmental plans and legislation.

Although the UK share of district heating is increasing, it is clear that markets still cling to the security of the gas network, shown by the substantial share of CHP in district heating networks. This will ultimately limit the ability to de-carbonise the heating sector and limit uptake of government subsidy. There is some suggestion that converting a natural gas CHP to a biogas CHP is viable, however the biogas supply chain is unproven in a U.K. context, and long term, sustainable alternatives should be considered for all future district heating networks.

The choice of low carbon, renewable energy supply to a district heating network can only be made after careful consideration to site requirements—available space, funding, supply and fuel security must all be considered for each new district heating network. That said, as a general rule of thumb, larger heating networks will opt for a co-generation system, while smaller schemes will opt for low-cost alternatives, such as ground source heat pump or air source heat pump. Scottish government incentives are now making the resources available for district heating to be further dispatched, however without encouragement to abandon the high carbon gas network, district heating will only primarily appear in new developments and likely with gas CHP.

Thermal management has taken a back seat to electrical demand prediction and dispatch, but is slowly increasing in research focus. This is necessary to improve the efficiency, and therefore lower the cost of district heating networks in the United Kingdom. This can range from simplistic tank storage to more complex phase change materials and load prediction. Future work must be able to address the challenges with energy planning of unpredictable human events and offer simple, easily applied techniques to thermal demand management.

District heating has been shown to prevail in countries with strong government support, not yet felt in the United Kingdom. In a time of political uncertainty, it is crucial for government backing to continue and expand. We recommend that this should focus on:

- Developing consumer awareness of DHNs
- Providing further incentive to low carbon projects (e.g., RHI)
- Develop necessary engineering skills and experience of DHNs
- Providing regulation and security for DHNs

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3. Roadblocks to Low Temperature District Heating

3.1. Introduction

Following the 1992 Kyoto Protocol, there has been an increasing amount of legislation dictating cleaner energy in the UK (e.g., the Climate Change Act 2008, the Carbon Reduction Commitment and the Energy Performance of Buildings Directive) [1-5] These frameworks are driving changes in everything, from energy efficiency measures to material choices in manufacturing, and the related carbon emission targets are forcing a significant re-think about power and heat production, supply and use within buildings. The UK government has implemented a net zero carbon policy which commits to being carbon neutral by 2050, in order to limit global warming to 1.5 °C above pre-industrial levels [3]. This compels the decarbonization of heat, which accounted for about 37% of UK carbon emissions in 2016 [6]. It has been suggested that in order to meet these targets, around 18% of heat in UK buildings will have to be met by heat networks by 2050, while less than 2% of heat is currently met from heat networks [6, 7].

Heat networks, or District Heating Networks (DHNs), across Europe are generally 3rd generation district heating networks (3GDHNs). These schemes typically operate above 80°C and are often supplied by a combined heat and power engine (CHP). 3GDHNs offered a significant energetic and safety benefit over previous generations, however with advancing technology and understanding, the move is now being made towards lower temperature and renewable technology-based heat networks, described as 4th and 5th generation DHNs. These steps must be used to encourage a sustainable energy market, which meets future heating needs.

Energy sustainability can be described from the World Energy Council’s Energy Trilemma. This ranks three metrics equally—environmental sustainability, energy security, and energy equity. Each criterion should be well balanced to achieve a robust energy system and can be used to monitor for potential trade-offs between the three weightings during a time of significant grid change and evolution, like the global transition currently taking place. Of the top five ranked countries, Denmark and Sweden have significant share in district heating [8]. District heating may pose energy security risks as a single, smaller provider becomes responsible for supplying a large number of users, yet this may be balanced by the ability to accept heat to the network from a much wider range of sources [9]. Using district energy schemes may also reduce the dependence of national energy imports, if the heat source is renewable (e.g., borehole, solar thermal etc.), more so than individual renewable heat as the source can be integrated to a larger number of users. DHNs can also increase the share of low carbon and renewable energy sources, however pricing and fair market strategies must be adopted to improve energy equity [10].

Although numerous reviews on district heating exist [10-17], very few have focused on the UK market, which is likely due to the relatively small share heat networks have in the UK heating market [18]. However, the UK government has made DHNs part of the energy strategy and so it is the aim of this paper to present a review which primarily focuses on the problems and challenges in implementing modern, low temperature heat networks into the current UK infrastructure. We do not give an extensive review of heat networks in general; our aim is to address some of the key technical challenges which must be considered and have not been discussed in detail elsewhere.

3.2. Background: 5G District Heating Networks

The UK's lack of district heating is now affording the opportunity to install higher efficiency networks than those already installed in DHN leading countries like Denmark and Sweden. 5th generation district heating is an emerging type of heat network which allows the exchange of heat and coolth between different buildings. This differs from the first four generations of heat network as the primary heat source is not from an energy centre but is from matching user heat demand with another user's cooling demand and wider integration of low-grade heat. Examples of this could be supplying the rejected heat from supermarket refrigeration to local residential blocks, capturing low-grade industry waste-heat or offset heat from data centre cooling. This moves from a consumer driven heat market to a much more active, distributed prosumer market. There have been a few suggested ways that this might work, with a variety of terms being applied such as balanced energy networks, ambient loop systems, smart thermal grids, neutral temperature networks and heat sharing networks. The supply temperature of heat in a 5G ambient network is generally accepted as in the region of 10–40 °C [19]. This is far below the required temperature for domestic hot water or space heating, so it is necessary to upgrade this heat, typically with a water to water heat pump. The real benefit of a 5GDHC ambient network is the flexibility to provide heating and cooling from a single supply line, which may offer improved efficiency and reduced capital investment over the alternative four pipe heating and cooling system. Figure 3.1-3.3 show the proposed distribution methods for a 5G 4-pipe system, a 5G ambient loop system and a traditional system.

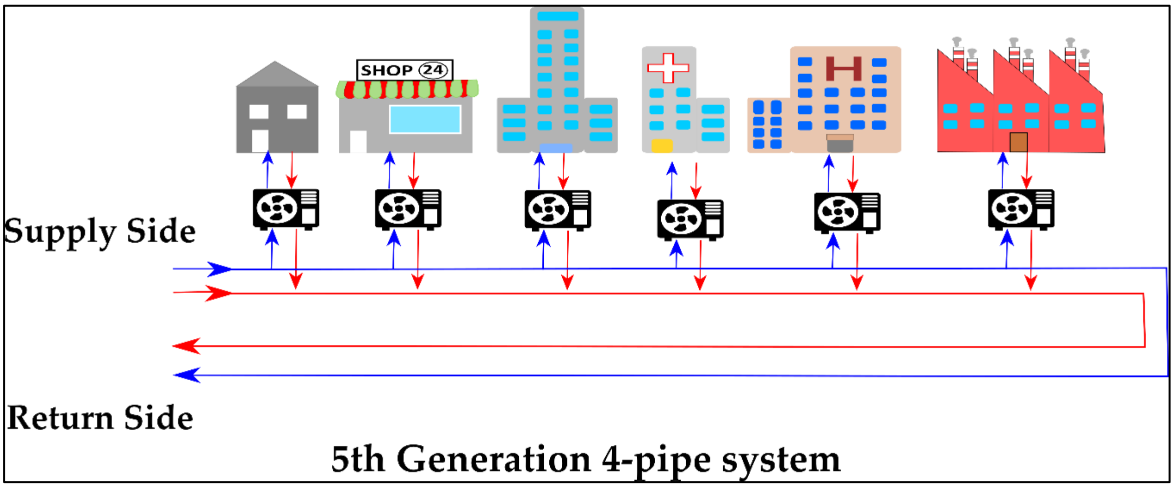

Figure 3-1 5th generation heat network with 4-pipe system. This system shows a variety of users accepting and rejecting heating and cooling into a 4-pipe system. This would operate at lower heating supply/higher cooling supply than traditional DHC loops.

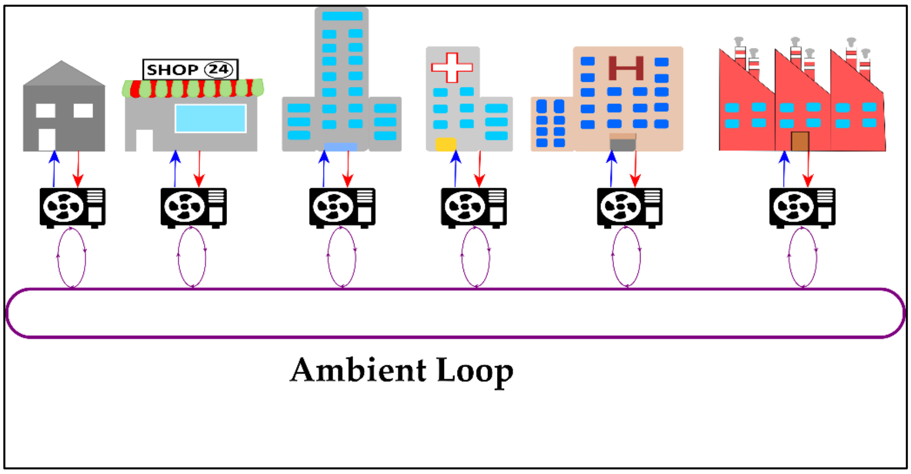

Figure 3-2 5th generation ambient loop DHC network. The purple loop operates between 10–25 °C and allows a source of both heating and cooling. Mixed users balance energy loads across the network, with little external heat supply.

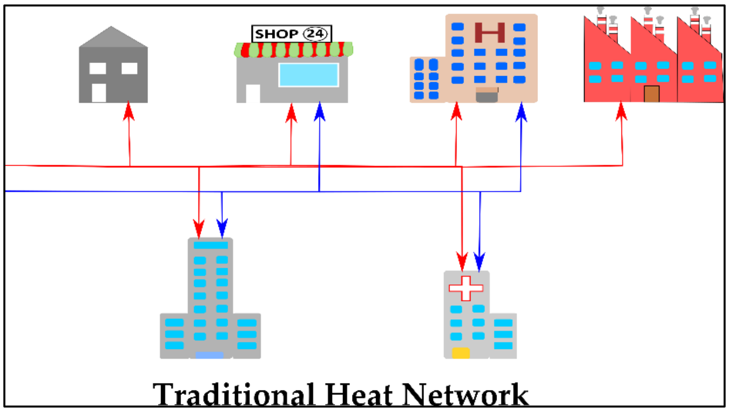

Figure 3-3 Traditional heating and cooling network, shown for comparison. Users have no ability to reciprocate energy across the network and are based on a purely consumer driver market.

5G networks will now face intense scrutiny to be able to enter the market on an even par with gas heating, or even traditional heat networks due to the novelty and lack of tried and tested schemes. There are many questions to be answered such as pricing strategies, how to prevent a monopoly market and equipment configuration. This may be an innovative solution, but energetic value is yet to be proven.

3.3. Background: 4th Generation District Heating Networks

4th generation district heating networks (4GDHNs) are most notably discussed and defined in [15]. Lund describes some key challenges to be addressed by 4GDHNs. These include lower distribution temperatures, smarter pre-fabricated components and flexible materials [15, 20]. Lund goes on to defines 4GDHNs as

> "*4GDH systems provide the heat supply of low-energy buildings with low grid losses in a way in which the use of low-temperature heat sources is integrated with the operation of smart energy systems…*"

It is unclear how well these objectives have been adopted in industry; however, these aims have been well discussed in literature. The aims can be broken into the following sections:

- Low energy buildings

- Low distribution losses

- Integrated low temperature heat.

Much of the work surrounding heat networks has been focused on reducing the supply temperature of the network, which has been suggested to relate to an energy saving of around 0.05 to 0.5 €/MWh·°C [21-26]. Gadd and Werner [27] present notable work to identify technical faults which persist in heat networks. They discuss fault detection in low temperature systems and divide heat network faults into three categories: construction faults, component faults and operation faults. In newer systems, construction faults are largely eliminated by the evolution of pre-fabricated energy centres and installations. Component and operation faults are much more likely to occur and are often related. Examples could be malfunctioning valve actuators, hot water temperature control or distribution pipe degradation [28]. These faults will be present in 5G networks as well, and so it is important to implement systems to reduce the likelihood of faults developing. It is likely that through reducing the temperature to 5G levels, many of these fault probabilities will be reduced due to lower temperatures and less harsh conditions.

3.4. Technical/Skills: Diversity and Sizing

Correct system sizing is paramount to an efficient and productive heat network, yet it is far too often that equipment is greatly oversized. This has been a problem for many well-intentioned DHNs, which has led to the network becoming poorly managed, inefficient and expensive.

During design phase, it can be easy to assume that the peak load on a network is simply the sum of the peak demand of each individual user, known as the aggregate demand. However, this is assuming that all users will require peak demand at the same time. For clarity, this means every user is simultaneously running hot water from every bath, sink and shower connected to the scheme when it’s −11 °C outside. The reality is that this never happens, yet some design engineers will still size the network for this as a worst-case scenario. A more realistic peak load can be accounted for by applying a diversity factor[2] to the domestic hot water demand, which reduces peak load from the aggregate load by taking into account the variability of user demands. The sizing method for

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[2] Diversity Factor=Peak Network demand/Sum of individual peak demands

traditional DHNs recommended by the heat network code of practice suggests Danish standard DS 439, however other methods have been used in the UK, such as BS 6700 and now BS 8558 or BS EN 806 [29-31].

Figure 3.4 shows a comparison of diversity factors for DS 439, BS 6700, BS EN 806-3 and German standard DIN 1988 [32]. It can be seen that using the traditional British method (BS 6700) will lead to vastly over-sized pipe networks and increased capital cost, while adopting the Danish standard can significantly reduce installation size. It is not common to apply diversity to space conditioning demands; external air temperature is the largest driver in heating demand and will have a similar impact on all users. However, the updated CIBSE Code of Practice (CP1.2) introduces a diversified space heating load based on Danish standards.

Comparing Figure 3.4 and Figure 3.5 show the significance of correct pipe sizing; oversized pipe can lead to significant thermal losses.

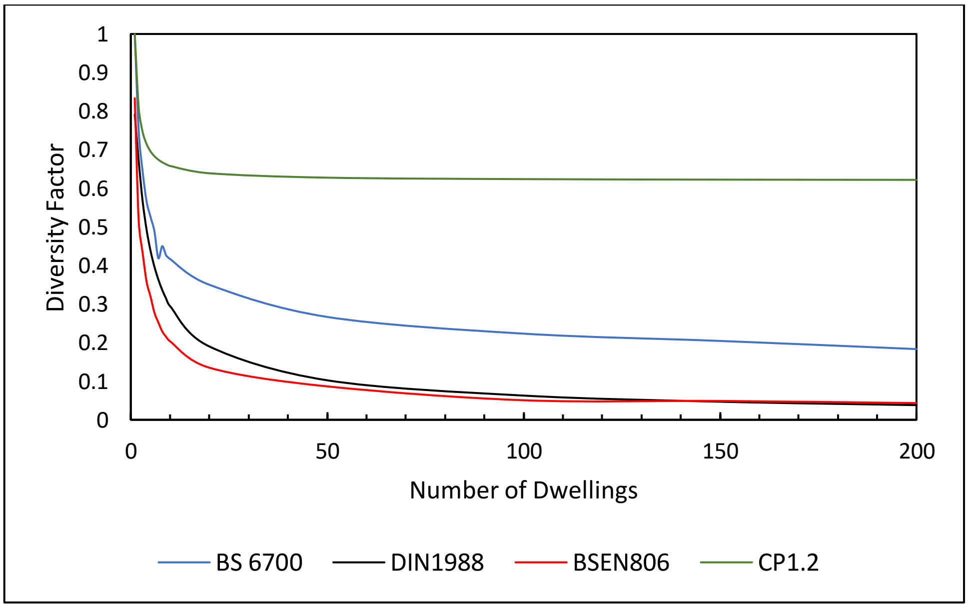

Figure 3-4 Comparison of diversity factors applied for water flow sizing, including DS 439, DIN 1988, BS6700, BSEN806-3 and CP1.2 Space Heating. BS6700 (orange) is clearly much higher than alternative methods for DHW, leading to oversizing.

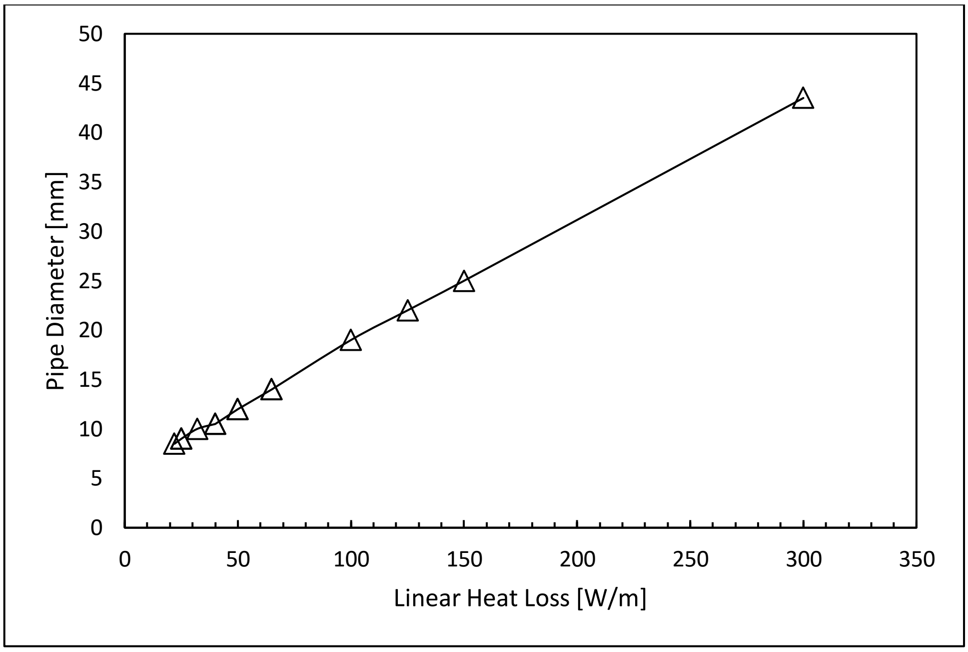

Figure 3-5 Heat loss per length of installed pipework from measured data.

Diversity should also be applied to sizing heating equipment, not just pipe sizing. The temptation to oversize a network can often be related to the economy of scale and the low cost of capacity, particularly with CHP and gas boiler systems, which can be seen from Figure 3.6. Heat pumps can be very expensive per kW installed capacity, however there is still an economy of scale. When Figure 3.6 is considered in the context of Figure 3.4, it is very clear that correct sizing is of paramount importance and there is clearly a balance between sizing reservedly and incurring un-necessary cost to developers.

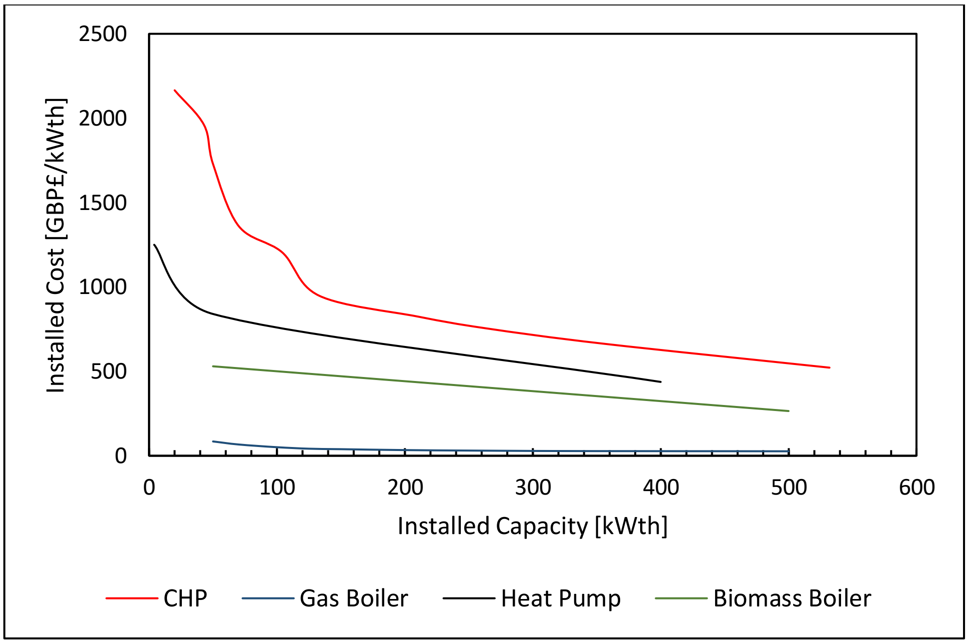

Figure 3-6 Graph of installed cost per kW thermal compared with capacity. The installed cost of CHP per kW is typically far less than that of a heat pump, yet gas boilers are even cheaper per kW but do not significantly reduce as capacity increase [33].

Oversized equipment has been identified in numerous studies as a significant cause of underperforming heat networks. This could be accredited to a lack of understanding at design stage, combined with apprehension around design failure. This is a clear challenge in the emerging heat network market and must be well investigated to produce affordable and feasible heat networks. This challenge is aggravated by the lack of low carbon options; currently only electrified solutions are available as low carbon and sustainable heat options, which are often significantly more expensive than a combustion based alternative.

3.5. Technical: Legionella and Legionnaire’s Disease

Legionella pneumophila is a pathogenic bacteria, which can cause legionellosis, a group of diseases including Legionnaires’ disease, Pontiac fever and Lochgoilhead fever. Legionella occur in natural water systems but can usually only reach significant levels when allowed to incubate and grow in a warm, purpose-built system, like a water pipe or storage tank (34). Legionella enters a strong growth phase between 25 °C and 45 °C (shown in Figure 3.7) which poses problems for low temperature heating systems [34-39]. Even in standard heating systems, 3rd generation storage tanks are often kept below 60 °C to reduce losses, creating a breeding ground for bacteria [38, 40, 41]. Control methods have been suggested such as copper-silver ionization, UV irradiation and chemical treatments. In the UK, guidance on Legionella control is provided by the Health and Safety Executive Approved Code of Practice. We discuss some of the more promising methods of legionella control here.

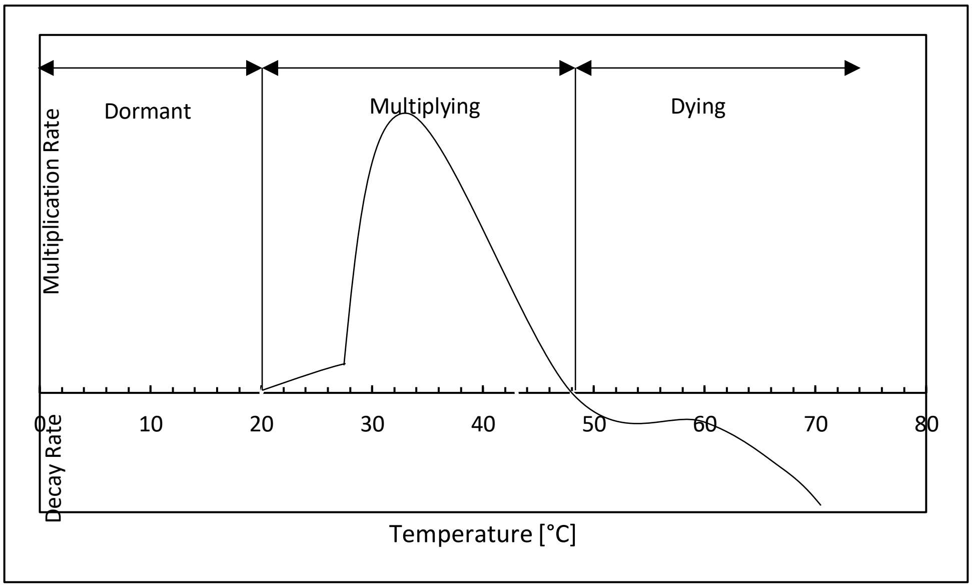

Figure 3-7 Diagram of Legionella growth temperature dependence.

Copper and silver ions are antibacterial and have been proven to control legionella growth in water systems [42-44]. This method electrolytically produces Cu^{2+} and Ag^{2+} cations from a small electrical current between copper and silver electrodes, which are introduced to the water system. The recommended dosage is 0.2–0.4 mg/L copper and 0.02–0.04 mg/L silver which may pose problems with local water quality compliance, and cases have been reported of legionella outbreak when the only method of treatment has been with Cu^{2+}/Ag^{+} below the recommended dosage [45-47]. In the UK, the upper legal limit of Cu^{2+} at outlets is 2 mg/L [48]. There is no legal limit of Ag^{+}, however the recommended upper limit is 0.1 mg/L. These limits are well above the required dosage for Legionella prevention, making copper/silver ionization a viable option. The cost benefits have not been well documented (either capital or operating), however for a typical 250 bed hospital the capital is estimated at approximately $50–10 k [44, 47]. This treatment system has the potential to work very well with low temperature district heating networkss, however further study would be needed to quantify influence this system would have on the energetic and economic case.

Chlorine dioxide has been used extensively to disinfect water for many years and has proven efficacy [49-52]. This is most commonly achieved by producing chlorine dioxide gas (ClO_2 (g)) on site and dissolving in the water system via a controlled dosing pump. While chlorine dioxide has been successful in limiting legionella growth, many studies have reported significant reduction only after several weeks or even years [50, 52-54].

Table 3.1 Summary of Legionella Prevention Methods[45, 55, 56].

Prevention Method	Advantages	Disadvantages
Chlorine Dioxide	• Widely used and well documented	• High operating cost due to high chemical cost • Not effective on established biofilms • Slow acting • Strong efficacy variation with water quality
Super-heat-and-flush	• Simple, well documented • No chemicals	• often fails in large systems
UV Light	• No chemicals	• Ineffective at distance • Not effective on established biofilms
Copper/Silver ionization	• Easy installation and maintenance	• May not comply with local water quality laws

	• Effective at high temperature • Can control other pathogens • Fast acting	• Requires regular chemical analysis to monitor ion concentrations • Regular maintenance needed for hard water systems

The efficacy of chlorine disinfection is strongly dependent on the chlorine concentration, contact time, water pH, temperature, organic solids concentration and the types of bacteria present [34]. This makes system monitoring vital to preventing legionella build up. The HSE recommend monthly checks of chlorine concentration at outlet taps, with dosing adjustment if the concentration is out-with the range of 0.5–1.0 mg/L. In the context of heat networks, this type of treatment is likely to be inefficient on its own and therefore an alternative used.

Ultra-Violet (UV) irradiation has been proven as a biocide and since used to limit legionella in water systems, however there are few cases of its application [57, 58]. Unlike other methods of prevention, after irradiation there is no lingering effect meaning that legionella is only prevented at the point of contact with the UV light. This is a significant disadvantage as it can lead to biofilm accumulation upstream of the treatment point.

There is clearly no conclusive method to eradicate legionella in pipework, and while 5G networks will likely distribute as a closed loop, biofilm prevention must be established to maintain strong heat transfer between the distribution loop and the end user loop. On the consumer side, heat pumps may still operate up to 60/65 °C for a short period on a daily cycle to prevent Legionella growth but smarter, more efficient methods must be further tried and tested.

3.6. Political: Low Energy Buildings

One of the largest energetic losses from a heating network is from the end user, or secondary distribution loop. To minimize energy loss and increase the efficiency of the network, building standards must be improved to be able to maintain thermal comfort within a building using a low temperature 4th or 5th generation DHN. The EU Energy Efficiency Directive (2012/27/EU) describes the energy efficiency target for 2020 and the Directive on Energy Efficiency2018/2002 describes targets for 2030. The legislation sets targets to member states but allows each member to meet these targets as they wish. This has caused significant disparity across the EU energy efficiency in buildings. Some countries have enforced significant and drastic targets, while others have opted for a less heavy-handed approach.

Denmark currently has one of the strictest low energy building standards in the world. By 2020, all new build homes must have an energy demand less than 20 kWh/m^2.annum and non-residential buildings a peak demand less than 25 kWh/m^2.annum [59]. In the UK, energy efficiency is typically based on carbon emissions, with standards varying across each member nation. In Scotland, there are no mandatory standards on energy usage and the standards are based on Section 7(a) of the Energy Performance of Buildings (Scotland) Regulations 2008 [5]. For residential buildings, each dwelling is given a rating based on current energy efficiency, environmental impact and then the potential room for improvement. This forms a compulsory energy performance certificate (EPC). At the moment, there is scarce incentive for private owners to improve EPC rating, however dwellings in the private rented sector must have an EPC band C or better by 2030.

Additionally, all new buildings must show that the proposed development has a building emission rate (BER) less than the target emissions rate (TER) [60]. The TER is based on a notional dwelling of the same dimensions as the proposed dwellings but using reference construction values. The TER can cause deviation in compliance from Scotland to England as the TER in Scotland is based on Section 6 of the Building (Scotland) Regulations, while England and Wales use the Building Regulations 2013 Part L. The Scottish regulations assume some form of renewable energy is used, which is hoped to encourage housing developers to include a renewable share in building design. However, many developers can circumvent this by improving the building fabric. Improving the building fabric can reduce the DER below the TER, without using clean energy. This loophole has been exploited for some time and must be addressed to encourage clean heat. Although renewable energy is not included in the TER calculation in England, the UK government has identified the same need for clean heat, and so has banned the use of gas boilers in new build homes from 2025. This may create a significant market for low temperature district heating, particularly in areas with high housing costs; for small dwellings, the additional plant space for individual clean heat solutions may be preventatively large. Therefore, heat networks may be preferred as the equipment in each dwelling can be reduced to a heat interface unit, which is much smaller than some alternatives.

District heating networks can only be efficient and economically viable when the end users have a good level of thermal efficiency. As the standard calculation method of EPC rating across the UK varies, a direct comparison of energy efficiency from EPC reports is difficult and widely considered inappropriate [61]. However, while a direct comparison cannot be drawn, general trends in energy efficient dwellings in each country can be considered in the context of DHNs. Figure 3.8 shows the 2017 energy efficiency for each nation in the UK, based on their respective methodology [62-65]. It has been suggested that a 4GDHN can be implemented to a low energy building, where a low energy building is defined as “a building that is designed to achieve or come close to the Passivhaus standard”[14, 66, 67]. For residential dwellings in the UK to meet this definition, as a rule of thumb will mean 15 kWh/m^2.year space heating demand or approximately 10% of a traditional dwelling’s annual heating energy [66, 68, 69]. Note that the definition of a low-energy building is not a hard definition and will vary from region to region. Passivhaus is considered one of the lowest energy demand building types yet may still have a poor EPC rating. The disparity is made clear in Figure 3.8. In many cases, a lower banded EPC rating can have a significantly lower energy usage in practice than a better rated building, shown in Figure 3.9. This shows a clear disconnect between evaluated energy performance and in-life energy performance, which makes it difficult for developers to easily assess suitability of low carbon technology from energy performance certificates; these EPCs are therefore not fit for purpose. It stands to reason that EPC criteria must be adjusted to give a more tangible, applicable and useful metric.

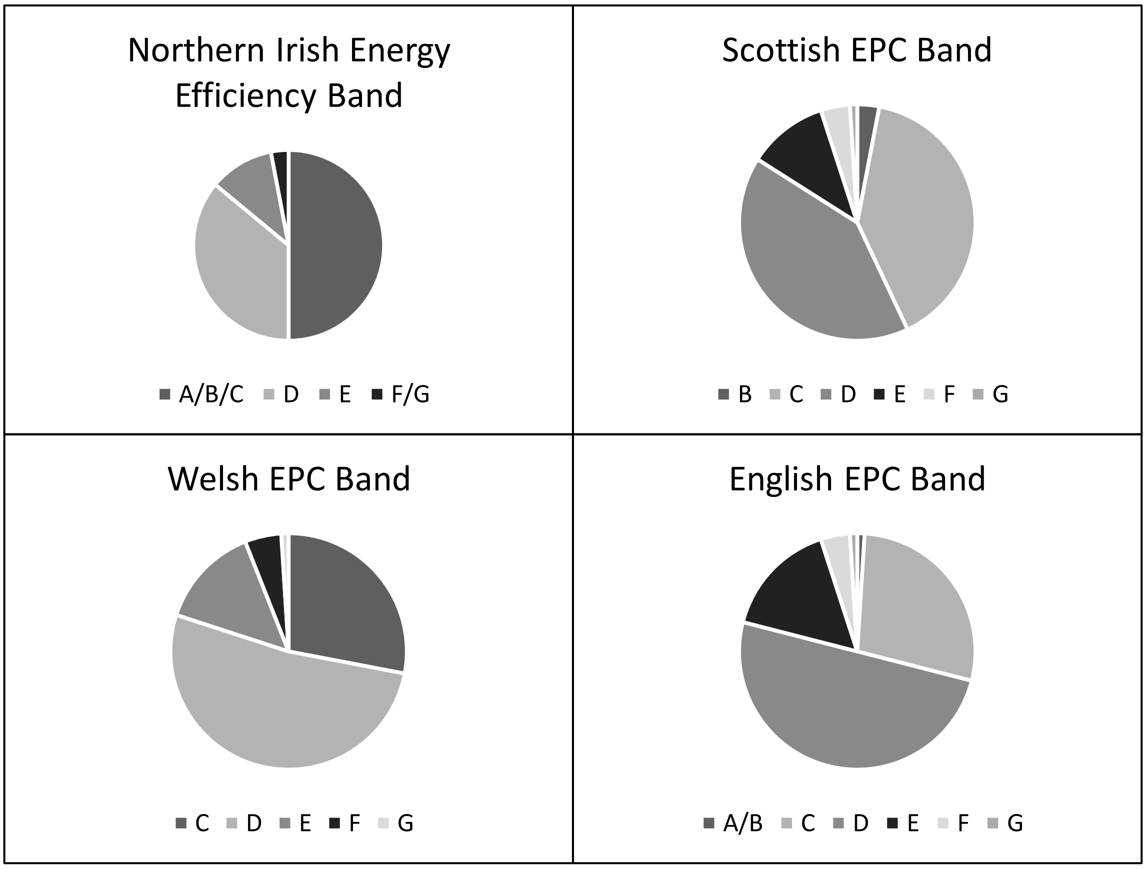

Figure 3-8 EPC Band of Domestic housing stock for 2017.

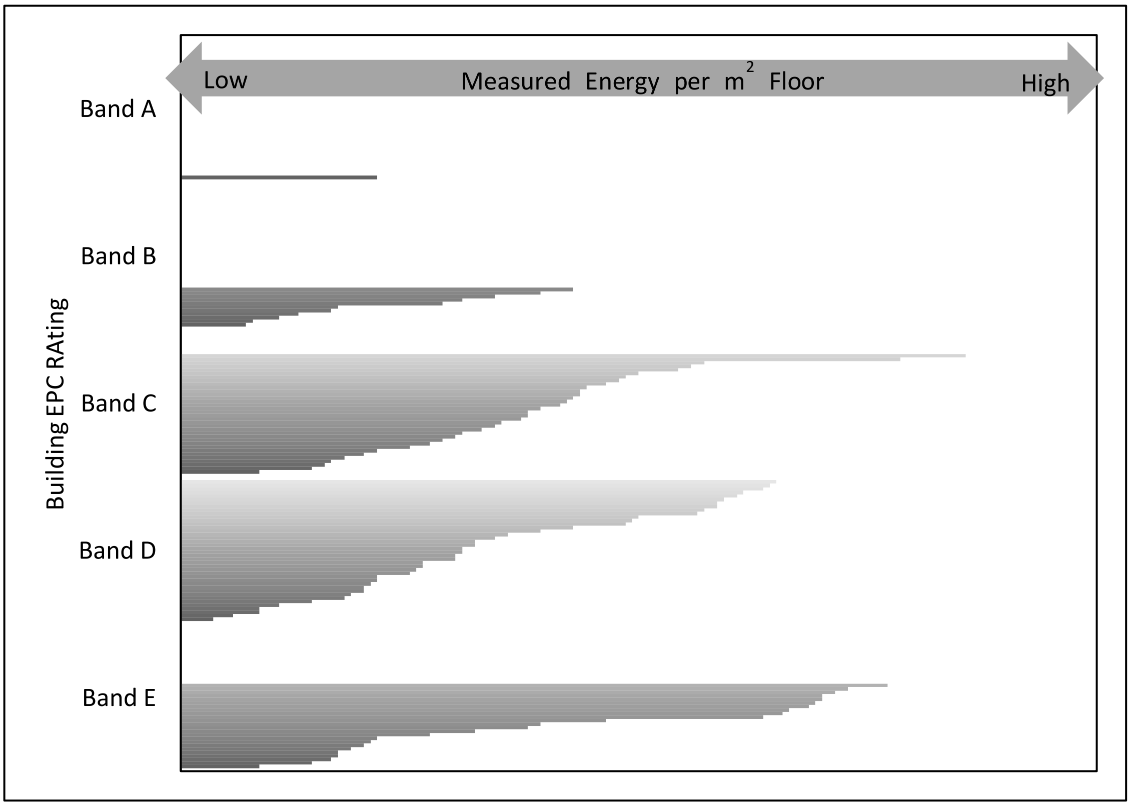

Figure 3-9 Measured energy performance compared with certified EPC rating.

District heating in the UK is in its infancy compared with countries at the forefront, like Denmark. For this reason, it is difficult to assess quantitively the steps necessary for 4/5GDHN compatible building stock; instead a qualitative approach can be adopted based on progress elsewhere.

There have been many studies on the compatibility of LTDHN with current building stock [23, 67, 70-81]. Several of these papers present an analysis of the existing radiator system [67, 81]. Tunzi, Østergaard [67] discuss the impact of LTDH on existing radiator systems for a typical 1930s Danish house. The work focuses on optimizing radiator performance by minimizing the radiator supply and return temperatures. This is a common theme in LTDH applications; however, consideration must be made to practical systems. To minimize the return temperature, the flowrate of water in the radiator system must be lowered. As the flowrate is lowered, the flow regime moves away from turbulent flow towards laminar flow, particularly when there is a large pressure drop e.g., when the radiator is far from the heating circulator or the pipe feeds a terminal unit. When the flow becomes laminar, heat transfer is grossly reduced. This should be considered in future work and lower bounds set on the supply flow rate in computational models. Flow guidelines are given in CIBSE Guide B1; for pipes up to 50 mm a minimum velocity of 0.75 ms^{-1} is set to prevent sedimentations [82]. However, many engineers will ignore these lower bounds in order to achieve the large ΔT, particularly in CHP systems where overall efficiency is much closer related to the ΔT between supply and return [83]. The work in [67] concludes that significant energy savings could be made in some buildings with LTDH in standard radiator systems, purely by smarter use of thermostatic radiator valves (TRVs) and mitigating human error. These lessons on human error can certainly be transferred, however a duplicate study using UK housing stock is necessary to assess the suitability for LTDH, due to the varying weather patterns, housing condition and human behaviour.

While there are certainly technical building challenges to be addressed in implementing 4GDHNs, the greatest challenges are in meeting the cost and in sourcing the technical skills and experience to successfully complete the job. A study from the department of energy and climate change (now BEIS), identified a critical financial barrier to obtaining feasibility studies for local authority-led schemes, while for private developers identifying suitably qualified consultants and accepted contract mechanisms was a key barrier [84]. By reconsidering the current criteria of energy compliance, easier access to well performing heat networks may be achieved by closing the performance gap and offering simpler initial feasibility assessment.

3.7. Low Grid Losses

Heat losses in DHNs can be from the production point, in distribution or from the end user. The key to reducing losses will always be an inherently efficient design. Heat losses from the end user are largely out with the scope of most energy managers, however this can be minimized through a well thought passive design. Heating networks are often managed by a third-party company on a network operation contract, however there is often ambiguity around the required efficiency measures the operators are expected to achieve. It is not uncommon for efficiency to be described from the percentage of non-useful heat that leaves the production area, however this can be misleading as when production is low, the percentage loss can appear high. This may encourage operators to increase heat production, therefore lowering the percentage losses, in order to meet contracted KPIs [85].

Distribution losses are described in the Heat Network Code of Practice for the UK (CP1) [86]. The code of practice is not compulsory for heat networks in the UK but is offered as a benchmark for best practice. Heat losses are largely described by objective 3.5, 6.4.4 and Appendix E. The recommendation is for heat losses in the network to not exceed around 10% but in practice, many network operators do not monitor or account for losses in the network in enough detail to take corrective action when needed. In cases where there is a surplus of heat, as is often the case with electrically-led CHP systems, there can be even less incentive to monitor heat loss. Other reasons can be:

- The network is managed by an external company and there is no contractual incentive to monitor losses

- The network manager lacks the skills to monitor losses

- The network is not fitted with sufficient monitoring equipment to calculate losses.

Water loss and quality is a common cause of heat loss in DHNs. Water can be lost along the network for a host of reasons, commonly:

- Leakage from terminal heat exchangers. This is common where there is a direct connection between the network and the end user heating system [20, 87, 88].

- Degradation of pipework. Often in older DHNs, management systems to monitor operational change and maintenance can be scarce. This can lead to pipes falling into neglect, especially when the network is substantial. Some examples of causes of degradation can be corrosion, mechanical faults (e.g., axial strain of pipework) and equipment ageing [87, 89, 90]. Degradation of pipework is a serious issue and even a small degree of wear and tear can cause significant damage and efficiency loss due to accelerated pitting corrosion, shown in Figure 3.10 [91, 92].

Figure 3-10 Example of extreme pipe pitting corrosion.

Water loss from the network will necessitate water replacement, which can be used as a guideline KPI of the network efficiency. CP1 does not set a benchmark for the number of water replacements, however it is generally accepted that less than one full water change per year is indication of a tight, well maintained and operated network [93, 94]. An estimate of the heat loss from carrier fluid leakage is given in Figure 3.11.

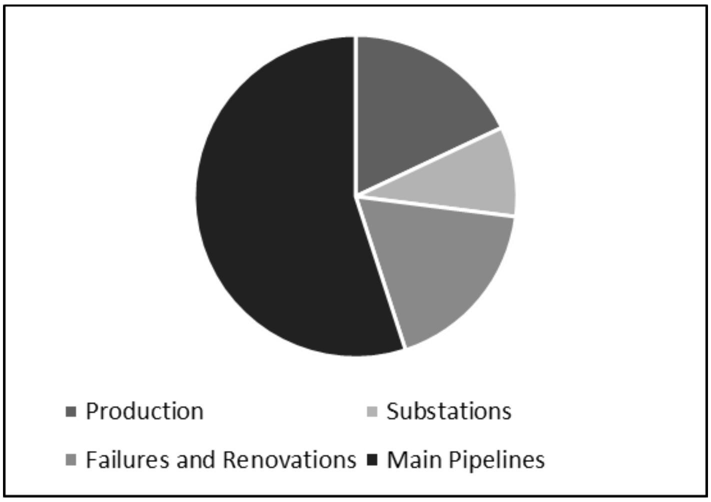

Figure 3-11 Source of heat loss from carrier fluid leakage [93].

It is unclear how vast an issue leakage is from heat networks, however, it is clear that many operators lack the training, understanding and equipment to control this. A summary of this discussion is given in Table 3.2, below.

It should also be noted that pipe insulation is a significant factor in reducing distribution losses. These are discussed in great detail elsewhere and so not discussed here.

3.8. Other Roadblocks

3.8.1. Policy: Electrification of Heat

A huge effort has been made to decarbonize electricity in the UK through assimilation of cleaner, renewable electricity production to the wider electrical grid. A similar approach is not currently possible for heating and the gas network, and so the electricity grid in the UK is expected to become cleaner than natural gas usage, shown in Figure 3.12.

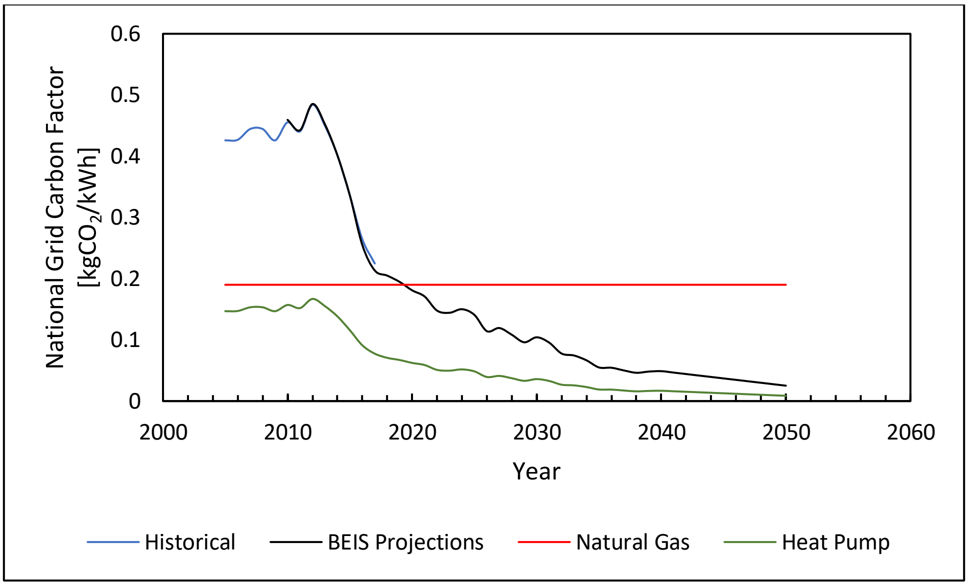

Figure 3-12 Graph of carbon equivalent predictions for UK electrical grid electricity, natural gas and heat pumps. Heat pump figure based on a CoP of 2.9.

To take advantage of the rapidly de-carbonizing electrical grid, heat production can be moved to an electrically led market, described as the electrification of heat. The most widely suggested method involves utilization of vapor compression cycle (VCC) heat pump technology, one of the most efficient, widely available heating and cooling methods [95, 96]. Love, Smith [97] suggest that the mass deployment of electrical heat is expected to have four critical challenges on both the transmission system operator (TSO) and on the distribution network operator (DNO). At a national level, the challenges relate to the increased peak demand on both the transmission line and the generation devices, and the grid ramp rate. The peak demand is the maximum instantaneous electrical demand on the network and the installed capacity in transmission and production must be able to meet this in order to continue providing a secure and stable electrical network. However, as heat is electrified, rather than drawing energy from the gas grid, this additional power will come from the electrical network. The increased electrical demand has been estimated to be 7.5 GW (14%) from a 20% uptake of heat pumps alone [97]. This does not account for any additional capacity required for other electrified process; primarily transport as electric vehicles become widespread. Others have suggested a peak increase of 25% peak demand using heat pumps compared with a 100% increase using direct heating; Oxford Energy suggest complete electrification of heat would require an additional 50 GW capacity at a cost of £100 billion [98, 99]. Some studies show a much smaller increase, estimating only 0.8 GW peak increase with the deployment of an additional 1 million heat pumps [100]. The ramp rate is the rate of change of electrical production over time. The UK electricity demand is not smooth; it has sharp, short peaks throughout the day, typically only lasting 2–3 h [100]. A load duration curve is given for December 2016 in Figure 3.13. The figure shows a fairly even distribution across the low power section and the high-power section, with significant peak durations at the end of the plot.

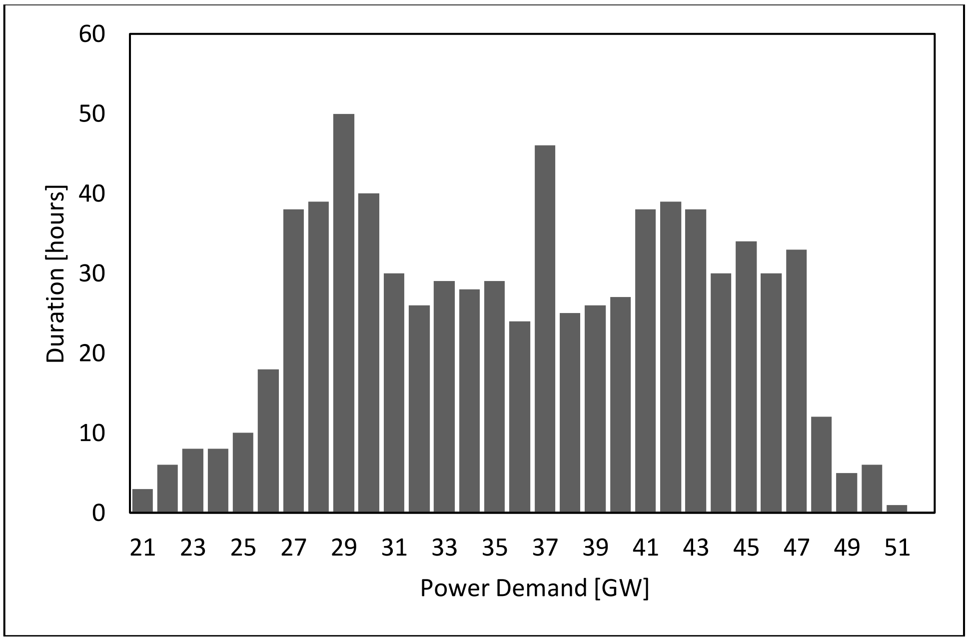

Figure 3-13 UK Load duration curve of electrical demand for December 2016.

While there is no clear census on the additional peak load, it is clear that transformation of the electricity generation and distribution must adapt with the heating sector to be able to truly deliver an integrated energy system. It is unlikely that low carbon heat will be realized without significant government incentive to reduce renewable heating to comparable cost with natural gas. This first requires a general government supported consensus on the best approach, which is unlikely to be realized any time soon with the current political climate in the UK over Brexit. Without government backing, it is difficult to enable any market to lead the decarbonization of the heating sector.

3.8.2. Policy: Procurement, Ownership and Contract Structure

DHNs in the UK are increasingly being identified by the National Health Service and local authorities as a low carbon and sustainable method to meet carbon reduction targets, yet project delivery can be daunting if not approached logically. This can be compounded by the lack of experience in heat network delivery for the UK. This section summarizes some of the challenges specific to DHN project delivery.

From an early stage, it is crucial to invest in an in-depth feasibility study. In particular, the study should include heat mapping, a building type study and consumer analysis. The economic case will be based on the number of consumer connections and so it is essential to understand the client base. This can be helped through market testing and consultation with local authorities. The procurement process can be made much easier if the initial feasibility studies have been completed in detail, allowing detailed risk analysis, defined liability and a clear established agreement for maintenance, performance and management.

Asset ownership in district heating can make this very difficult. If the network is to be installed in a completely new development, then this can be simplified but thought must still be given to the incoming property owners. In the past, many new homeowners have claimed they were not made aware the new property was connected to a heat network, giving the homeowner significantly higher than expected bills with a long commitment period (e.g., 20 years).

Table 3.2 Summary of Distribution Loss Reduction Methods.

Measures to Reduce Distribution Losses			
Measure	**Description**	**The Good**	**The Bad**
Reduce Supply Temperature	Lowering the supply temperature has been shown to be energetically favourable The supply temperature to the grid is reduced.	• Lower supply temperatures will reduce heat losses • Possible in-life	• Lower temperatures may not be compatible with all users.

Increase supply/return difference	A greater difference will give better utilization of heat produced and reduce losses in the return pipe.	• Pumping energy and capital cost are reduced. • Possible in-life	• Requires lower flowrates which may not be compatible with end user heating systems or building quality.
Design for smaller Pipe Sizing	The developed design should use the smallest pipe size possible, while considering the balance between smaller pipes and greater pumping costs.	• Smaller pipes will reduce heat loss (lower heat transfer area). • Lower capital cost	• Must be from the design stage • Smaller pipes will increase pumping costs. Electricity is more carbon heavy than heat in most networks, so optimization needed between the reduction in heat loss and the cost of pumping.

Network Structure—Reduce network length	Reducing length will reduce heat losses	• Lower capital and installation costs	• Must be from design stage
Network Structure—Smart user placement	By placing large demand users at the start of the network, high grade heat is delivered to larger users and lower grade to lower users.		• Smart supply routes may lead to a longer network. This approach will necessitate further feasibility studies adding cost to early stage design. • Must be from the design stage
Reduce Water Leakage	Leaking pipes can cause significant heat loss	• Reduced operating cost • Increased system efficiency	• Requires good monitoring systems

In developments connecting to existing infrastructure, each owner must be consulted to connect to the network. This becomes problematic where the tenant does not own the property; the property is leased through the local authority (if they are not the project instigator), leased through a housing association or privately rented. Even then, where works must be carried out on shared communal space (such as a communal stairwell) the individual owners may not be able to offer permission to work. These additional discussions will necessitate additional consultation time and should be duly considered to begin negotiations in a timely fashion, to limit impact on revenue and increase connections.

3.9. Conclusions and Future Work

District heating technology has come a long way from low efficiency high temperature and pressure steam, but with fast approaching carbon targets and climate change, it is now more important than ever for policy makers to seriously consider and implement high efficiency heating and cooling networks to decarbonize the heating sector. Fourth generation heat networks offer a promising step in the right direction, but fifth generation must not be ignored if we want to create a future-proof, flexible and robust heat market. For either 4th or 5th generation to gain a foothold in the market, it is necessary to integrate with thermally robust and efficient buildings to accommodate for lower supply temperatures. As DHNs become more widespread, clearer energy performance metrics must be adopted to be able to easily and cost-effectively determine which buildings are suited for low temperature heating, be it from DHNs or other renewable sources.

We have identified and discussed challenges in minimizing distribution losses; a critical step to efficient DHNs. These losses can be managed through regular monitoring and maintenance of the network. These losses are primarily from operation and component failure. Operational failure can be minimized through stringent management guidelines and operator training, while component failure must be continuously monitored. The framework for EPC and energy efficiency should be reconsidered to reflect the developing blend of renewable technology and the growing performance gap. The methodology should encourage clearer and more applicable energy ratings. This could offer a simpler initial feasibility study and therefore reduce costs to prospective developments.

With increased efficiency and lower supply temperatures, other problems have emerged. Legionella control methods are available for low temperature heating applications but, to the best of our knowledge, cost and energetic assessments have not been carried out. This is compounded by the lack of experience from design engineers in correct sizing approaches for emerging equipment applications. This will have significant adverse effect on the stability of the electrical network if not correctly managed.

To summarize, we conclude that:

- Investment must be made to upskill current talent in the UK to design, build, and operate district heating networks to best practice

- Care must be given in equipment sizing. Applying the "gas boiler" mentality can be expensive and leads to inefficiently designed systems

- Current energy performance metrics (EPCs) are not fit for purpose. These should be replaced with a suitable alternative which places emphasis on energy intensity, rather than carbon intensity.

- In-life performance assessment is crucial to bridge the performance gap between design and reality. Installation of sufficient monitoring equipment is crucial for this to be successful.

We can conclude from this review that a serious and significant overhaul of practices and principles for heating system design and management is the only way to tangibly tackle the decarbonization efforts. Future work should focus on an in-depth evaluation of all widescale and likely low carbon heating technologies to be able identify the best fit for both the current and future heating and electrical market; only then will a truly integrated system be achievable.

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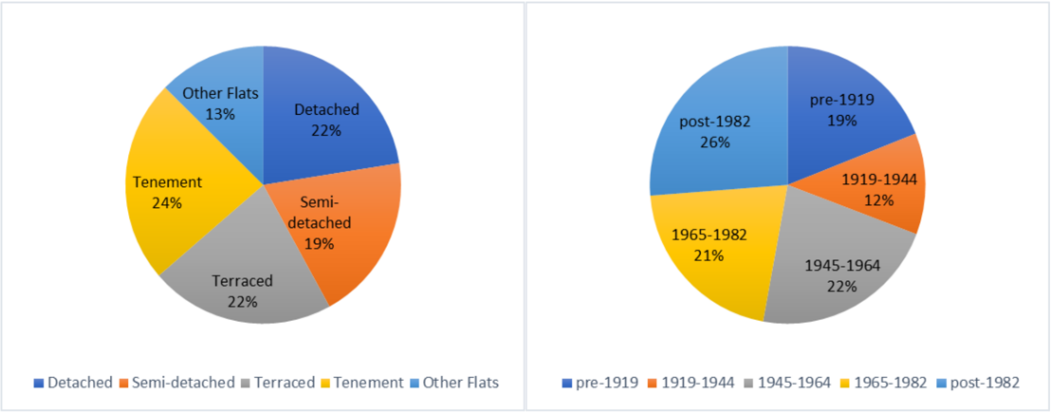
4. An Investigation into the Limitations of Low Temperature District Heating on Traditional Tenement Buildings in Scotland

4.1. Introduction

Residential energy use has changed significantly from the 19th century until now, moving from solid fuel combustion (e.g. coal/wood stoves) to a predominantly gas heating market, which totals 64% of domestic energy usage in the UK in 2017 [1]. The Scottish government has set ambitious targets to provide 11% of non-electrical heat demand by renewable sources by 2020, and for 35% of domestic heat to be provided by renewable sources by 2032 [2]. The government also aims for all Scottish homes to have an energy performance certificate (EPC) of at least band C by 2040, where “technically feasible and cost effective” [2]. In Scotland, the greatest number of dwellings by type is tenement flats, and more than 74% of housing stock was built pre−1982, as shown in Figure 4.1 [3]. This suggests, in order to achieve Scottish government targets, the greatest focus must be on modernizing existing housing stock, rather than new housing.



(a) **(b)**

Figure 4-1 Breakdown of Scottish dwelling type by (a) number and (b) year built, in 2017 [3].

Limited work has been completed to the assess the suitability of existing residential buildings to connect to a district heating network (DHN); examples shown in [4–11]. Brand and Svendsen [6] discuss the necessary upgrades to existing stock in order to integrate a low temperature district heating network (LTDHN). They show that for a typical single-family, Danish house from the 1970s, small refurbishment can allow the district heating supply temperature to drop from 78 °C to 67 °C, and below 60 °C for 98% of the year. This study uses a home already connected to a DHN and compares the energy demand between the traditional DHN and a LTDHN. The paper shows promising results with minor investment. However, while the paper acknowledges the need for water disinfection for supply temperatures below 60 °C, it is difficult to know how this will influence the overall efficiency, carbon savings or cost. Østergaard and Svendsen [8] provide an investigation into the use of LTDHNs from the 1930s in single family houses, a similar study to Brand and Svendsen [6]. This study considers the influence of replacing critical radiators, and found that while 50% of the case studies could be converted to LTDH with minor renovations, 50% would require substantial work. This work is not directly transferable to the UK due to different building styles and weather patterns, but does, however, show the first steps in considering options for existing housing stock.

Wang and Holmberg [11] discuss retrofitting Swedish multi-family buildings from 1965–1975 with low temperature heating and a heat recovery ventilation system (FTX ventilation). While this discussion is limited, it does show that savings could be made on space heating—albeit with significant renovations, which would likely be out-weighed by the significant cost of improving/installing the DHN substation, installing the ventilation system, and improving the air tightness, as is recommended by the paper.

Burzynski et al. [12] provide a valuable insight to space heating and domestic hot water demands from newer tenement flats (built 2007–2010) connected to district heating schemes in the UK. The study makes use of metered data provided by one of the big six energy providers, Scottish and Southern Energy (SSE), to present floor area normalized energy usages for space heating and domestic hot water. A standard heat interface unit in a UK dwelling with district heating will only measure the total heat supplied to the property and will give no indication of the split between space heating or hot water. To find this split, Burzynski et al. [12] first applied a regression analysis to estimate a base temperature for heating degree days. The heat supplied on the calculated non-heating days was then assumed to be only for hot water, giving a baseline usage which can be subtracted from the total heat for the rest of the year to differentiate between space heating and hot water heating. The results of Burzynski et al. [12] do not correlate with SAP 2005 or SAP 2009; this could be due to an underestimation of heating in the methodology of the authors, which differs from the SAP method for estimating energy consumption, however this performance gap has been well documented elsewhere [13–17]. This is a significant piece of work for the UK district heating market, but will have limited applications to a significant majority of housing, which does not follow the Building Regulations part L or Section 6 (Scotland). The flats in this study have a district heating supply, but it is unclear if this has been from build or retrofitted later (although likely from build, due to the age of the dwellings).

Ovchinnikov et al. [18] give a comparative review of low temperature heating systems with a focus on the practicalities of the Russian building sector. In this paper, the authors discuss the merits of being able to use smaller radiators with a higher supply temperature, before going on to discuss the low energy efficiency of this approach. The authors mention the priority of addressing consumer awareness of energy usage. The authors discuss the challenges and obstruction of 4G heat networks by obsolete 3G networks. This is an interesting insight into the contrast between the challenges of heat network integration in the UK and abroad. While the UK is installing new networks, many other countries must consider how to best improve existing networks. The paper concludes that low temperature heating can be used in existing Russian housing, however, significant energy efficiency can only be achieved with vast refurbishment and building improvement. In a further paper, using an IDA Indoor Climate and Energy (IDA ICE) tool, Ovchinnikov et al. [19] provide a dynamic model and assessment of Russian building regulations and the feasibility of low-temperature heating for residential buildings. The study investigates four hydronic space-heating configurations with either a high temperature supply (75 °C) or low temperature supply (45 °C). The paper concluded that a heat pump supply could offer good energy savings for many of the case studies and operating conditions.

Peeters et al. [20] assess heating control in residential buildings for a Belgian case study. The study describes the current heating practice in Flanders by first summarizing previous housing surveys and boiler conditions. This data is then used in a TRNSYS model to evaluate the efficiency of gas boiler systems with varying levels of insulation. The case study models a terraced house with a multizone thermostat and night set back and concludes that optimal efficiency can be achieved when a flexible heating design is used, which is able to cope with large variations in heating load. A very similar study was performed by Liao et al. [21] in a UK context, however this focused on non-domestic users and no new information is provided for UK domestic dwellings.

On considering the current state of the literature, we present in this study the transient system simulation tool (TRNSYS) models, where we consider the necessary building improvements for a typical Scottish tenement flat to be connected to a district heating network or a low temperature district heating network. Lowering the supply temperature of a heating system requires careful consideration to the building condition. Therefore, we first consider and discuss the minimum supply temperature achievable to maintain a reasonable thermal comfort level at different levels of building renovation. The calculated minimum supply temperature is then used as the set point for the LTDH river source heat pump loop. A parametric analysis is provided, showing the energy and carbon savings achievable from district heating in each case study. The aims of this study are to:

1. Through dynamic computational modelling, assess the minimum radiator supply temperature which can maintain a reasonable thermal comfort in a Scottish/UK domestic dwelling, under various building conditions.

2. Assess the potential energy and therefore carbon reduction of implementing the minimum chosen supply temperature.

3. Qualitatively assess the feasibility of a river source heat pump to meet the demand of domestic heating.

The modelling tool chosen is TRNSYS. TRNSYS is a simulation environment which can be used to extensively model HVAC and building systems, amongst other things. The user can select from a range of pre-installed “types”, which computationally represent physical components. At each time-step, the TRNSYS kernel feeds inputs to the different types that produce the outputs. The process is described in further detail in the TRNSYS documentation [22,23].

4.3. Methodology

The methodology is as follows:

1. Define the case study.
2. Develop a building model.
3. Assess minimum supply temperature for each case using a TRNSYS model.
4. Use chosen supply temperature to assess operability and control operation of river source heat pump.
5. Assess energetic and carbon benefits.

4.3.1. Case Studies

There are many choices available to improve the energy efficiency of a dwelling. For this study, two of the most common home improvements were chosen for consideration—double glazing and wall insulation. The case studies are summarized in Table 1.

Table 4.1 Summary of case studies.

Case Number	**Single Glazing**	**Double Glazing**	**Insulation**	**No Insulation**
1	X			X
2		X		X
3	X		X	
4		X	X	

The chosen case study is a traditional sandstone tenement flat, a common building type in Scotland. Tenement walls are typically solid wall, with no cavity. This makes insulation difficult, as it must be either internal or external. External insulation is not a recommended choice as it will inevitably change the appearance of the building. Internal insulation is possible, however, it will remove a small amount of internal space. Internal insulation is the only feasible option and therefore is the only one considered here. The supply temperature is varied from 60–100 °C to mimic a broad range of typical DHN supply temperatures.

4.3.2. Building Modelling

To be of any significance, the building choice must be typical tenement housing stock; unfortunately, due to the age of the buildings, accurate and updated plans are not publicly available. The building layout was chosen from available plans of a typical tenement and is therefore not specific to any site (however, many tenement buildings will follow this structure). As the plans are not updated, they do not include any consideration to building modifications or renovations; however, as the modelled dwellings are less than 150m^2 floor area, they can each be modelled as a single thermal zone. This makes any error due to un-accounted for renovations likely to be insignificant.

The building geometry was produced from building plans of a typical 20th century Glasgow tenements, shown in Figure 4.2. The geometry was created in Sketchup (previously Google Sketchup), shown in Figure 3, and TRNSYS3d. TNSYS3d is a Sketchup extension which allows the construction types to be defined in Sketchup (e.g. external wall, window, roof etc.) and then exported as a *.idf file, which is then imported to TRNBuild, where the thermal properties of the building can be implemented. TRNBuild produces a *.b18 file which can then be used in the TRNSYS simulation studio with Type56 multizone modelling component.

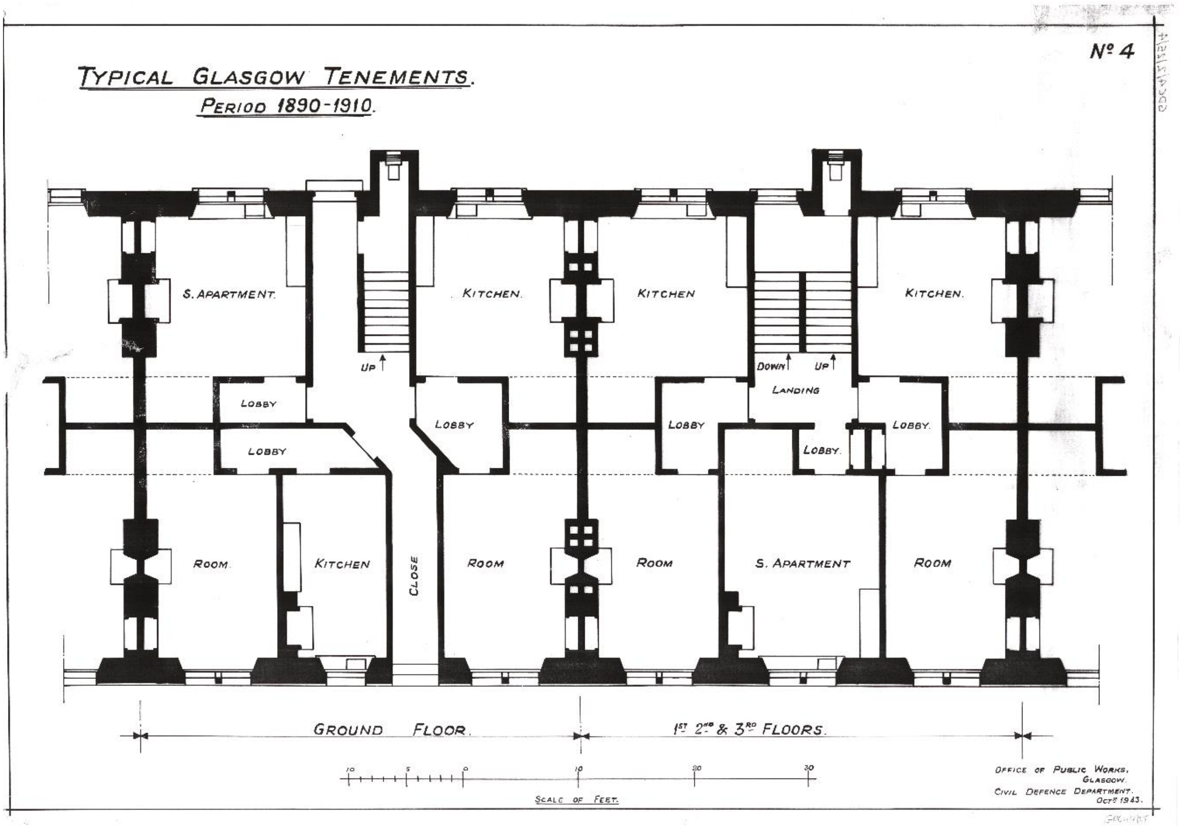


Figure 4-2 Typical Glasgow tenement plans. Reproduced with permission from Glasgow City Archives.

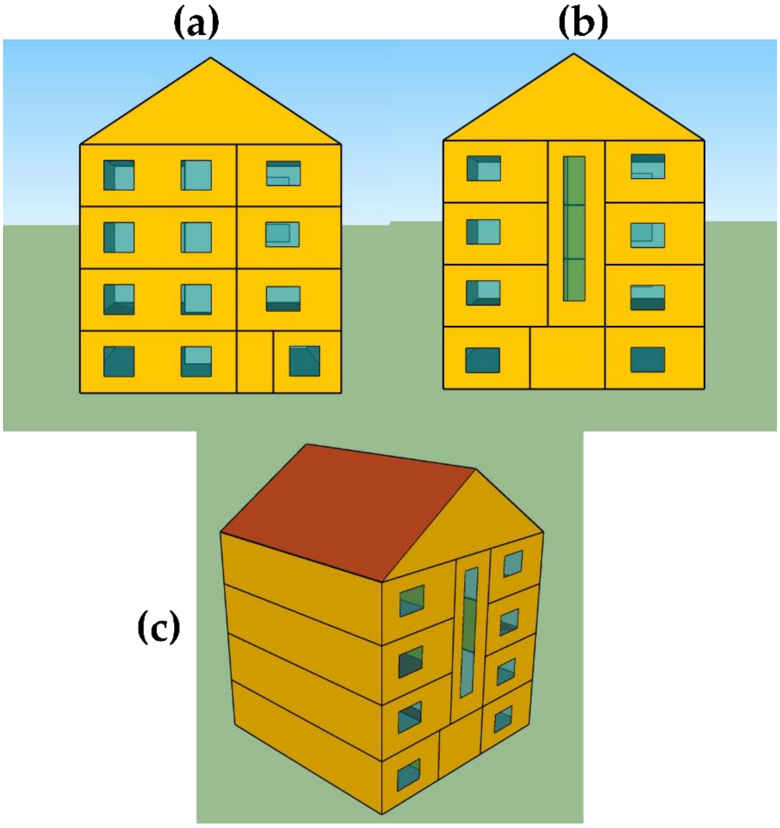


Figure 4-3 . (a) Front, (b) back, and (c) isometric view of modelled tenement.

The single close of flats contains eight dwellings. Only one close is shown, although it is typical for tenement blocks to have 20 to 30 closes.

The initial TRNBuild construction types chosen are shown in Table 2.

Table 4.2 Initial heat transfer co-efficient of TRNBuild constructions.

Construction Type	Materials	U value (W/m^2 K)
EXT_WALL	Plasterboard Sandstone	1.0
EXT_ROOF	Plasterboard Slate Plasterboard	2.5
ADJ_WALL	Brick	2.4
ADJ_CEILING	OAK	2.4
GROUND_FLOOR		0.78

Data is not available to consider how many properties exist with original fixtures and structures, however, the considered modifications are shown in Table 3 with thermal conductivity (U) values [24].

Table 4.3 Heat Transfer co-efficient for building materials.

Building Component.	Thermal Conductivity (W/m^{2}K)
Single-glazed wooden windows	5.8
Double-glazed PVC windows	1.2
Solid wall—no Insulation	1.0

Solid wall—insulated	0.18

It is assumed that the roof has been replaced since initial construction, however, since this is not part of the upper dwellings, it is not considered with renovations.

4.3.3. Minimum Supply Temperature

For each dwelling, there is a minimum supply temperature of space heating, dependent on the dwelling's ability to retain heat and the radiator capacity. Using TRNSYS, this is determined for each building construction case, as shown in Table 1. These temperatures are then used as a basis for the following sections. The TRNSYS model used to determine the minimum supply temperature is shown in Figure 4.4 and Figure 4.5. The expanded macro shown in Figure 4.5 is the same for all "Flat X" macros. Radiators in the UK are typically designed for an 82 °C supply and 71 °C return temperature and are supplied by gas boilers. Energy and cost savings are therefore calculated against this as the base case [25].

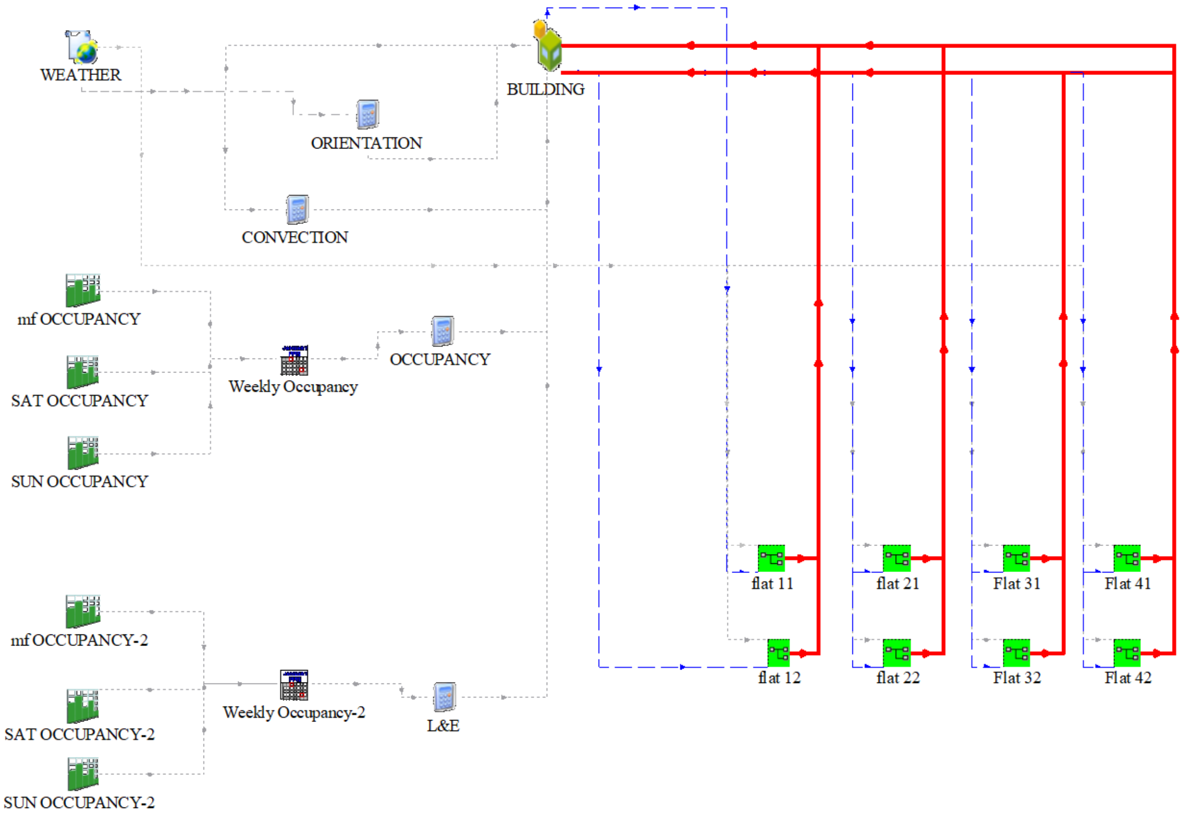


Figure 4-4 TRNSYS Simulation Model. Blue lines show cold streams, red shows hot streams and grey shows auxiliary streams (occupancy schedules, control signals etc.).

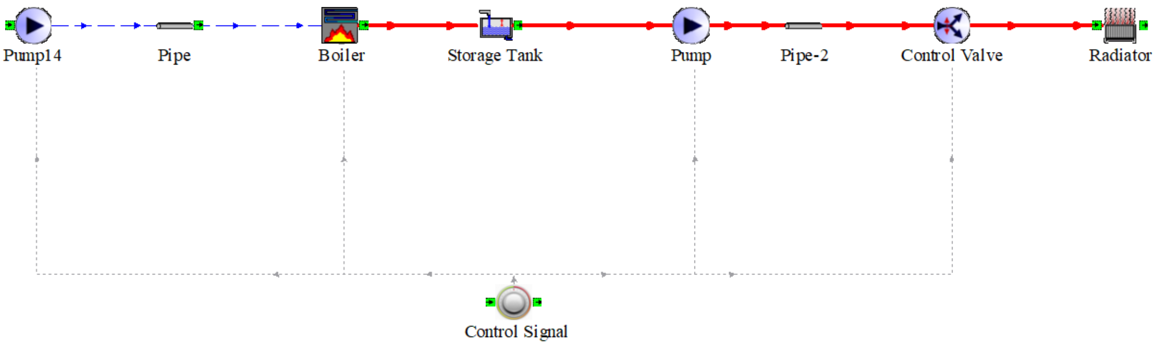


Figure 4-5 Expanded TRNSYS Model macro.

The air set point temperature of the dwellings is chosen as 20 °C during occupied periods, based on a generic occupancy schedule [6,26]. To maintain the set point temperature, the radiators must balance the thermal losses from each dwelling. The energy balance used in the building model is given in Equations (1)–(3) [27].

$$\dot{Q}_{ConGain} = \dot{Q}_{surface} + \dot{Q}_{infil} + \dot{Q}_{vent} + \dot{Q}_{ICG} + \dot{Q}_{CAG} + \dot{Q}_{Solwin} + \dot{Q}_{solshade} \qquad (1)$$

where $\dot{Q}_{ConGain}$ is the air node convective heat gain, $\dot{Q}_{surface}$ is the convective surface gains, $\dot{Q}_{infil}$ is the infiltration gains, $\dot{Q}_{vent}$ is the ventilation gains, $\dot{Q}_{ICG}$ is the internal convective gains, $\dot{Q}_{CAG}$ is the convective air gains from other thermal zones, $\dot{Q}_{Solwin}$ the convective solar gains from external windows and $\dot{Q}_{solshade}$ is the portion of convective gains from absorbed solar radiation on shading devices. There is no mechanical ventilation and so:

$$\boldsymbol{\dot{Q}_{vent} = 0} \qquad (1)$$

It is impossible to accurately determine air exchange between flats without further study, so it is assumed to be negligible for the purpose of this investigation. Therefore

$$\dot{Q}_{CAG} = 0$$

The heat addition from infiltration is given as

$$\dot{Q}_{infil} = \dot{V}\rho c_p(T_{outside\ \ air} - T_{inside\ \ air}) \tag{2}$$

where $\dot{V}$ is the volumetric flow rate of air, ρ the air density, c_p the specific heat capacity and T the temperatures of the outside and inside air.

The radiative fraction calculations are complex and explained in detail elsewhere [27–29].

4.3.4. Water Source Heat Pump Design

The heat supply technology chosen is a river source heat pump, due to Glasgow’s large resource of river water. This is designed to operate by extracting 3 °C from the supply river water and deliver it to the main water. Although there are examples of water source heat pumps being able to condition water streams to 80 °C, WSHPs are typically only rated by manufacturers to 60/65 °C. For this reason, the heat pump is designed to condition the load stream to 60 °C. The load stream is then supplied with auxiliary heat from a gas boiler until it reaches the design supply temperature. No consideration is given to parasitic electrical load in the COP calculations (e.g. the electricity required to pump water to the heat pump). Figure 4.6 shows the adjusted TRNSYS model.

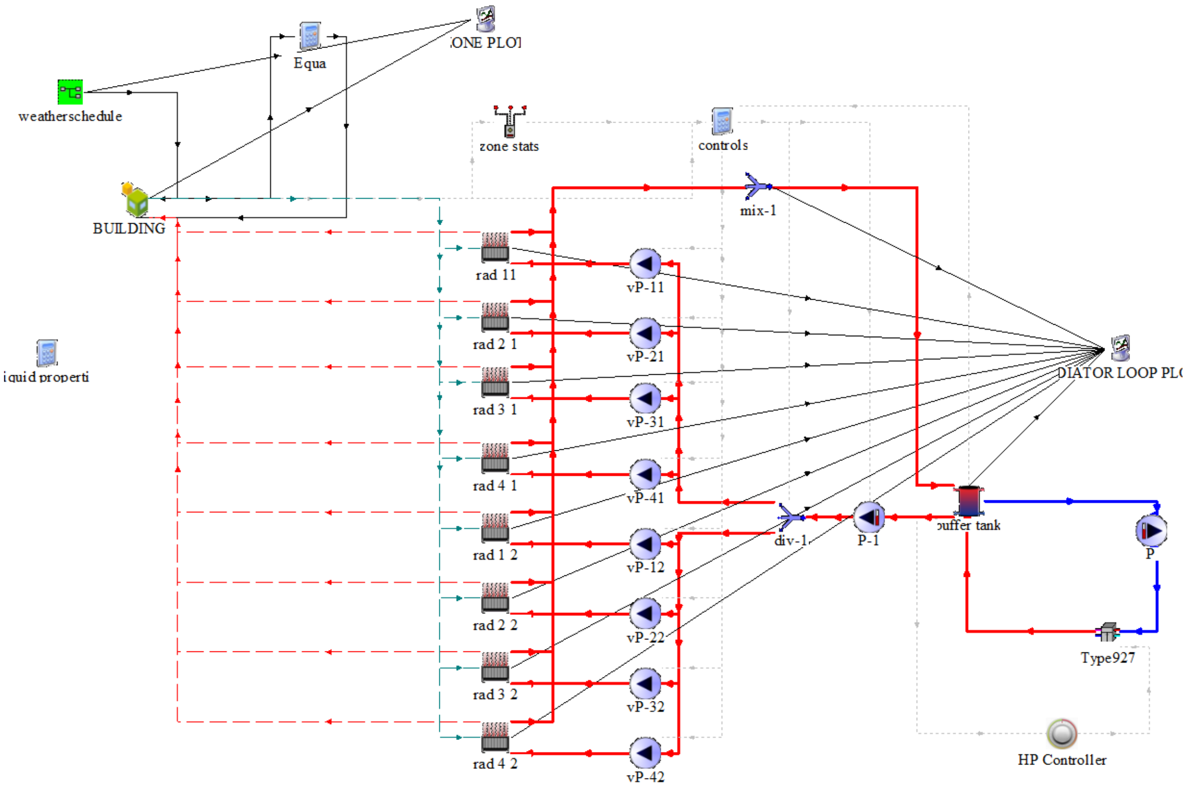


Figure 4-6 TRNSYS model used for heat pump supply modelling.

Figure 4.7 and Figure 4.8 show the daily average temperature and cross-sectional flow of the River Clyde at Daldowie (NS 67154 61642). There are currently no limitations imposed by the local authority on heat extraction, however, for operational reasons the heat pump is controlled to extract 3 °C from the abstracted river flow and to switch off when the return flow to the river falls below 2 °C. This sets a lower operating temperature of 5 °C on the abstracted river stream. When the heat pump is off, the radiator loop is conditioned to the set point by the gas boilers only. A simple proportional controller is used for the purposes of this study, but a more sophisticated control system could make it possible to store heat prior to the river dropping below 5 °C.

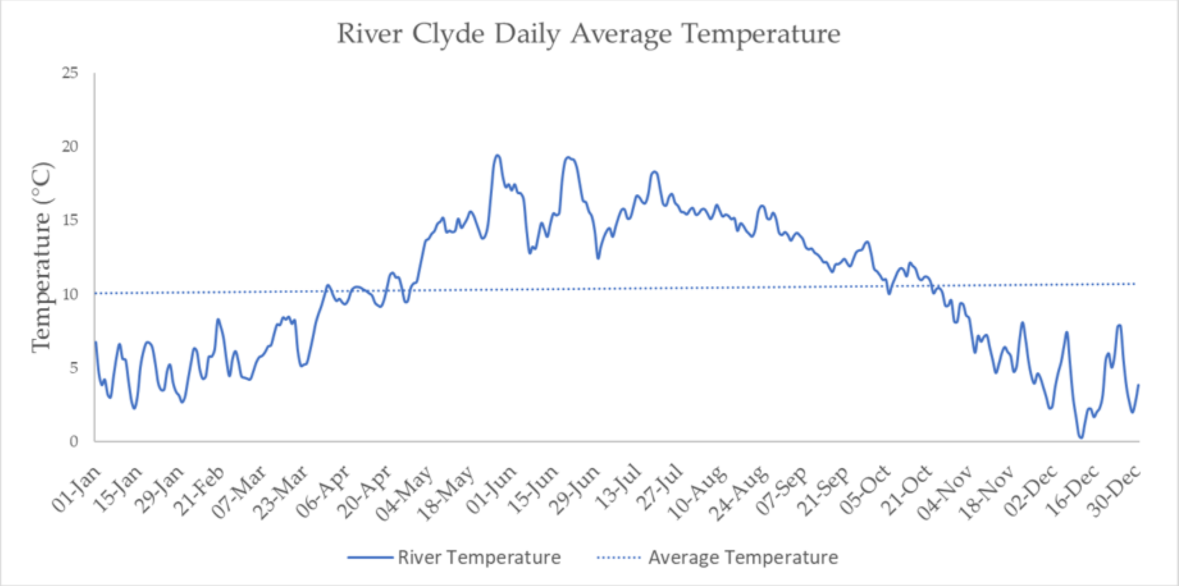


Figure 4-7 Average daily River Clyde water temperature at Daldowie for 2017.

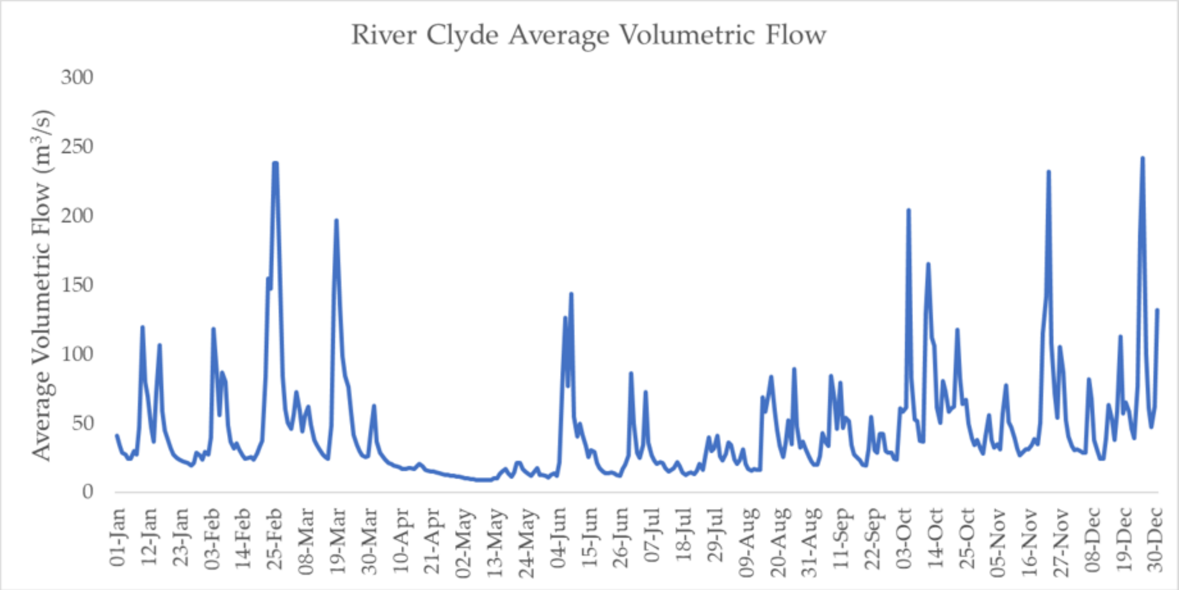


Figure 4-8 River Clyde average daily volumetric flow at Daldowie for 2017.

4.3.5. Radiator Loop

The radiator circuit is a closed loop feed, going from a small buffer tank to the radiator system and then back to the tank. The intermediate components shown in Figure 4.5 control the supply rates and pressure in the loop. Each dwelling is designed with 5kW of radiator capacity, which is typical of this dwelling type. From radiator sizing guidelines, this is undersized for the property—a common problem in UK housing.

4.3.6. Carbon Benefits

A standard carbon calculation is used to determine the carbon footprint of two energy systems. The first system is where the entire thermal load is met by a gas boiler. It is assumed that a condensing boiler is used with an efficiency of 90% [30,31]. The second system uses the heat pump to initially heat the water to 60 °C, and then uses a gas boiler to reach the set point temperature.

4.4. Results

4.4.1. Minimum Supply Temperature

Table 4 shows the average percentage of timesteps where the heating system could not maintain the set point temperature. Figures 4.9–4.12 show the percentage of timesteps where the zone air temperature fell below 19 °C. Figure 4.13 shows the heating power across the sample year.

Table 4.4 Average percent of timesteps below 19 °C across all dwellings.

Average % of timesteps below 19 °C				
Supply Temperature (°C)	Case			
	Case 1	Case 2	Case 3	Case 4
60	88.7	49.0	37.0	30.7
65	81.7	39.7	27.0	20.9
70	72.9	30.6	18.2	13.0
75	61.0	22.0	11.3	7.4
80	47.7	14.9	6.5	3.8
85	34.7	9.2	3.2	1.7
90	22.4	5.2	1.3	0.5
95	12.9	2.8	0.4	0.1
100	7.6	1.4	0.1	0.0

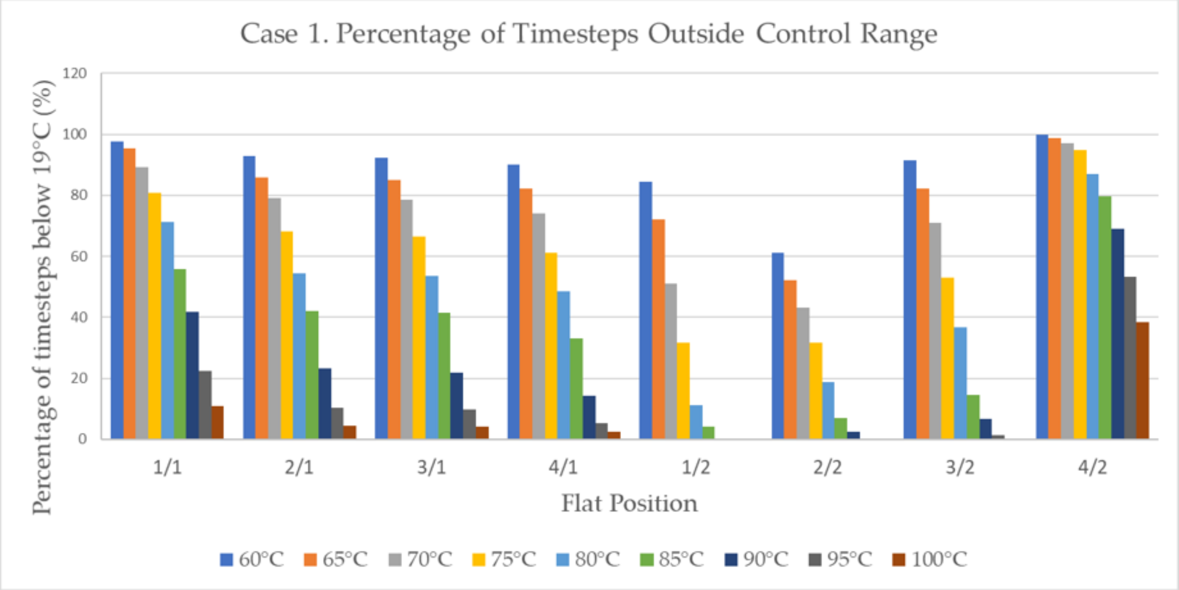


Figure 4-9 Case 1: no insulation and single glazing.

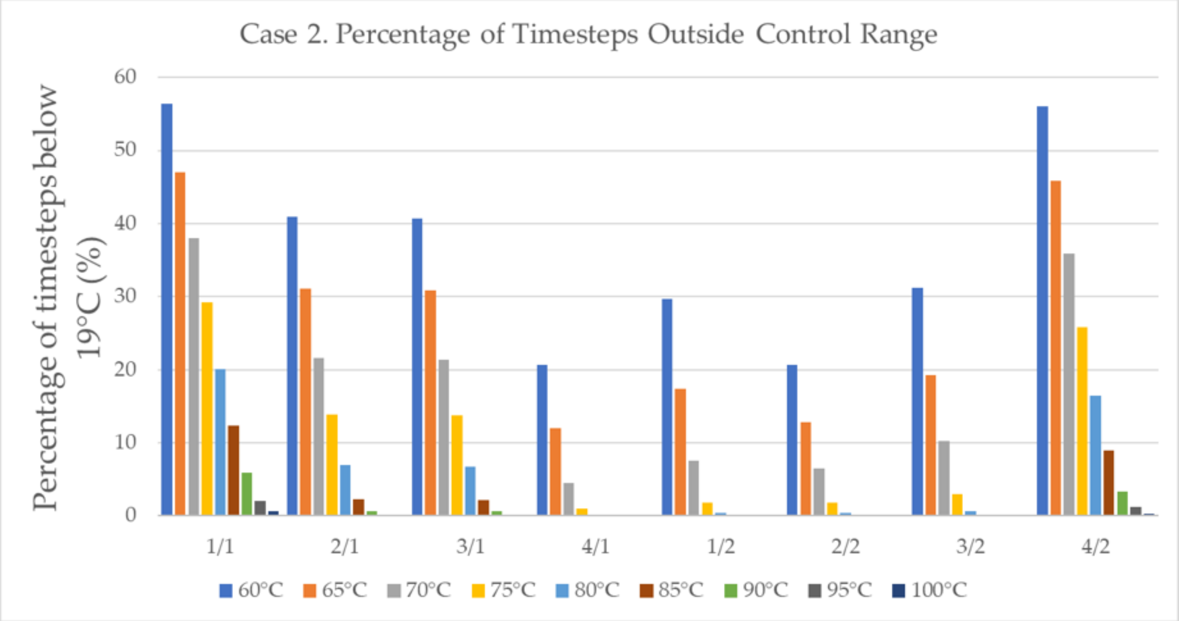


Figure 4-10 Case 2: no insulation and double glazing.

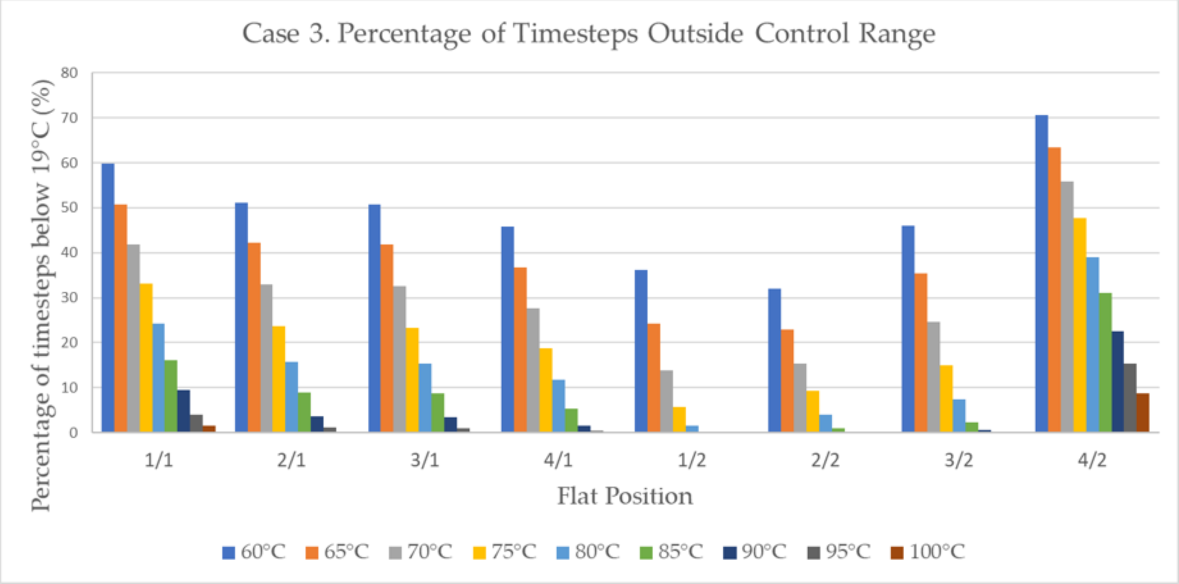


Figure 4-11 Case 3: insulation with single glazing.

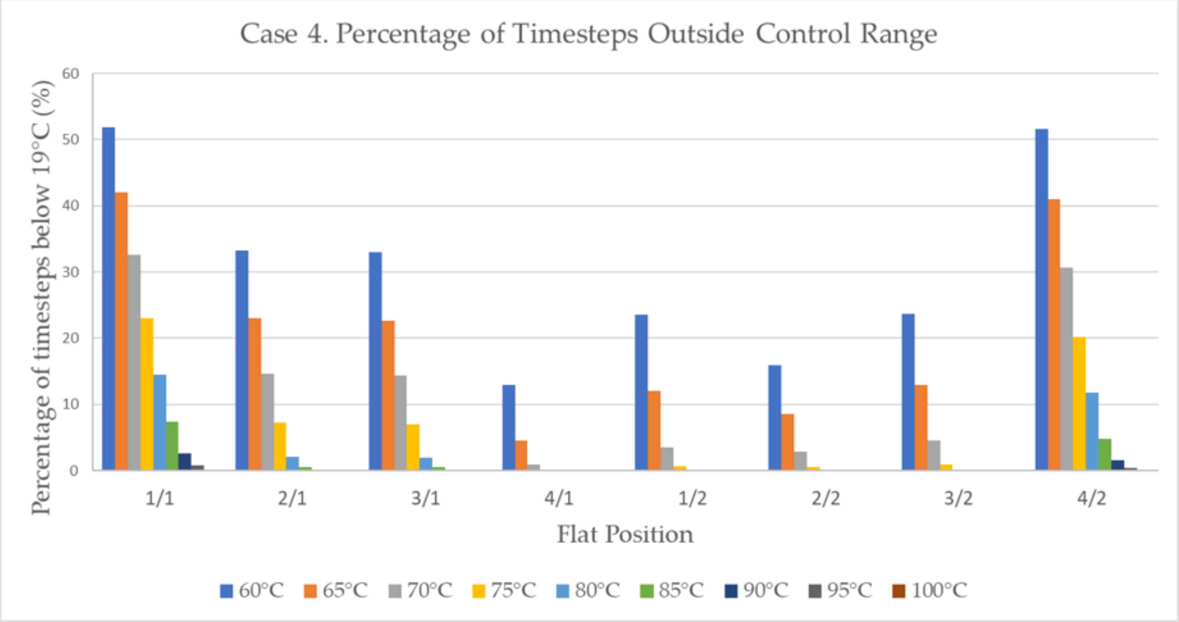


Figure 4-12 Case 4: insulation and double glazing.

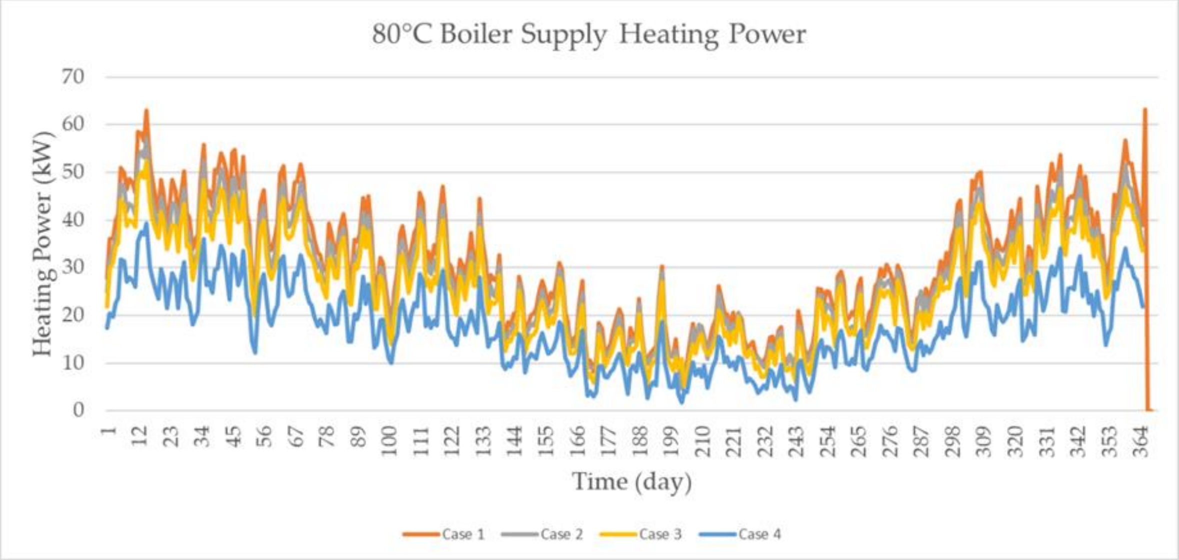


Figure 4-13 Case by case comparison of heating power demand at 80 °C.

4.4.2. Carbon and Energy Savings

The following tables show the computational results from modelling the gas boiler and heat pump energy usage at each case study. Table 5 shows the minimum achievable supply temperature chosen from Section 3.1, which is then used as the set point temperature for the modelled radiator supply. Table 6 shows the energy usage and saving when space heating is met only by the gas boiler for the base case of 80 °C supply and for the chosen minimum. Table 7 shows the electricity and gas usage when the space heating is met by the river source heat pump and supplemented by gas boilers. Table 8 shows the equivalent carbon emissions for each case. All tables show results for the full block of flats.

Table 4.5 Minimum supply temperature.

	Minimum Temperature
Case 1	80
Case 2	75
Case 3	70

Case 4	65

Table 4.6 Gas boiler energy usage.

	Gas Boiler Energy Usage (MWh)		
	80 °C	Minimum	Saving
Case 1	271	271	0
Case 2	249	234	15
Case 3	227	219	8
Case 4	154	150	4

Table 4.7 Boiler and heat pump energy usage.

	Boiler and Heat Pump Energy Usage (MWh)						
	80 °C Supply Temperature			Minimum Supply Temperature			Saving
	Gas	Electricity	Total	Gas	Electricity	Total	
Case 1	161	41	202	161	41	202	0
Case 2	145	37.3	182.3	133	41.7	174.7	7.6
Case 3	132	36	168	120	33	153	15
Case 4	75.4	32.5	107.9	51	36.8	87.8	20.1

The carbon emissions are based on the 2018 UK government conversion factor; 1 kWh electricity is 0.283 kg CO_{2e} and 1 kWh natural gas is 0.204 kg CO_{2e} [32].

Table 4.8 Carbon emissions.

Carbon Emissions (ton CO_{2e})						
	Boiler			Boiler and Heat Pump		Saving
	80 °C	Minimum	Saving	80 °C	Minimum	
Case 1	55.284	55.284	0	44.447	44.447	0
Case 2	50.796	47.736	3.06	40.1359	38.9331	1.2028
Case 3	46.308	44.676	1.632	37.116	33.819	3.297
Case 4	31.416	30.6	0.816	24.5791	21.9	2.68

4.5. Discussion

4.5.1. Minimum Supply Temperature

Figures 4.9–4.12 show the percentage of time steps with non-zero control signal that are below 19 °C. The minimum supply temperature is chosen as the point where the system can meet approximately 80% of the demand. The additional 20% needed can be met through thermal storage; these demand side management techniques are well documented elsewhere and therefore not considered here. For dwellings with no insulation or double glazing, this does not drop significantly until the supply temperature reaches 85 °C (a typical operating temperature of domestic radiators in the UK). For smaller district heating networks, the supply temperature is often kept below 80 °C to allow the use of polyethylene or polybutylene pipes in the distribution network; these pipes can only cope with a maximum of 90 °C flow for short periods of time [25]. If thermal losses in the distribution system are considered, the temperature in the network will exceed 90 °C for a significant duration, meaning pre-insulated steel carrier pipes will likely be needed. This greatly increases the project costs. An alternative is to operate the network at a lower temperature, in order to minimize capital cost through the use of polymer piping and supplement the conditioned stream from a pre-existing heating system within the dwelling. This would add costs only to the end user, which is not preferable. Given the financial significance of dwelling connections to the network economic model, it is not recommended to adopt this approach. It can therefore be concluded that, for dwellings that are poorly insulated with low quality windows, internal improvements must be made before connection to a district heating network becomes a viable option.

When the dwelling has been fitted with insulation but no double glazing, a 70 °C flow can, on average, meet the heating demand for over 80% of the year. On addition of double glazing, a 65 °C flow can meet demand for around 79% of the year – largely similar to Case 3 with a 70 °C flow. Double glazing without insulation (Case 2) can only reach 78% of demand at 75 °C. As is to be expected, the lowest supply temperature is achievable with double glazing and insulation. The addition of insulation offers a 36.1% improvement on air temperature maintenance, while the addition of double glazing offers only 28.3% improvement in Case 1. Case 4 (both insulation and double glazing) offers a 39% improvement in Case 1, but only a 3% improvement in Case 2. It is therefore clear that, while the greatest improvement is with double glazing and insulation, the improvement by the double glazing is only marginal. The choice of double glazing should be considered based on the economic or carbon case.

4.5.2. Water Source Heat Pump Supply

In the sample year (2017), the average daily river Clyde temperature falls below 5 °C for 16% of the year. On these days, heating is supplied entirely from the gas boilers. For UK tenements, this necessitates a reliance on the gas boilers during this period; the boilers cannot be removed from the dwellings. While this is common in the UK, the dependence on gas can be phased out with improved thermal storage and demand side management.

For Case 1 (no insulation, single glazing), the supply temperature could not be reduced and so remained at 80 °C. When the water source heat pump is used with the gas boiler, a 25% reduction in energy and 20% carbon saving can be achieved.

From Table 7, it is clear that a reduction in total energy usage does not relate to a linear reduction in electricity to the heat pump. This is because the return temperature from the radiators is typically above the heating set point of the heat pump (60 °C), meaning that the heat pump is used to heat the radiator loop initially, but not continuously, during heating.

4.6. Conclusions[3]

The UK faces challenges to decarbonize the domestic heating sector, but has few choices to do this. The best options will offer significant carbon benefits and be competitively priced to the current heating market. This work has presented a dynamic

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[3] Assumptions have been made in the model around the occupancy, thermal properties, and system efficiencies. At the time of the study, this data was not available. It is acknowledged that this error could be significant enough to alter the numerical values of the study, however it is unlikely to significantly alter the overall findings of the work.

transient system simulation tool model of a typical tenement flat in the UK, one of the most common dwelling types. From this work, the following conclusions can be drawn:

The minimum supply temperature of domestic radiator systems, and therefore district heating schemes supplying tenement buildings, is strongly dependent on the building condition. Wall insulation can be difficult to install in solid wall tenement blocks but can yield a 16% energy saving on space heating per year, without lowering the supply temperature. Double glazing had less of an impact in this study but may be more significant in buildings with a greater window to wall ratio.

Tenement blocks in poor condition are unlikely to be able to connect to a district heating scheme, due to the high supply temperatures giving rise to a significant cost of carrier pipes.

In cases where no supply temperature reduction is feasible, energy and carbon savings can still be made from integrating low carbon technology. In Case 1 with heat pump supply at an 80 °C set point, energy consumption was reduced by 25% and the carbon footprint by 20%.

When building conditions permit, supply temperature can be reduced to around 65 °C and could yield almost a 70% reduction in space heating.

While there are currently no restrictions in Scotland on river heat abstraction, this is heavily dependent on the local laws.

4.6.1. Future Work

This work is presented as the start of a conversation around district heating connections for traditional housing in the UK. For this work to progress:

A substantial building condition survey of UK housing stock is needed to afford a better appreciation of the potential of low temperature heating

Greater government incentive must be offered for privately owned dwellings to decarbonize heating

Further minimum supply temperature studies of other dwelling types are needed, potentially offering a tool for developers to easily assess the minimum feasible supply temperature for retrofitted projects.

4.8. References

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5. Identification of key performance indicators and complimentary load profiles for 5th generation district energy networks

5.1. Introduction

Climate change has far reaching consequences and can only be mitigated by concerted global efforts. The current lack of international consensus is problematic for taking effective action. The UK emitted the equivalent of 460 million tonnes of carbon dioxide as greenhouse gases (GHGs) in 2017, with almost 40% from natural gas used for heating [1]. It has legally binding commitments to reduce GHGs to Net Zero by 2050, making decarbonisation of the heating sector a key priority [2, 3]. UK 1st and 2nd carbon reduction targets (budgets) have been met, the 3rd is on track, but efforts to meet the 4th by 2027 are lagging [4]. As part of a government carbon plan, the UK has committed to development of district heating networks (DHNs) and determining the likelihood of mass electrification of heat [5]. This poses an interesting opportunity for 5th generation heat networks, which combine mass electrification, heat networks and energy sharing between buildings.

DHNs in the UK are fairly uncommon, providing only 2% of overall UK heat demand [6]. Almost 90% are supplied by natural gas boilers and Combined Heat and Power (CHP). This may have been a good alternative to coal in the past but as more coal fired power plants are decommissioned and renewables enjoy increasingly wide scale penetration, the carbon intensity of electricity is projected to fall below that of natural gas by 2035. Some estimates suggest electricity will be as much as 140gCO_{2e}/kWh lower than natural gas by 2050 [7]. This will encourage the electrification of heat, moving away from natural gas boilers towards direct electric heating and electrical heat pumps. The majority of operational DHNs in the UK are largely 3rd generation (3G) networks [8, 9], with high supply temperatures (circa 90°C) [10], high thermal losses [11], and are difficult to manage [12, 13]. It has been shown on many occasions that reducing the supply temperature and incorporating a larger share of low-grade heat into DHNs can offer improved efficiency but will still face many of the same challenges as 3G DHNs [14-19]. These problems include high thermal losses (particularly in low population density areas), few connections to the network (connection uncertainty), and difficulty in procuring usable low-temperature sources. These challenges could be addressed by 5th Generation (5G) DHNs which allow heat and coolth to be exchanged across a network via an ambient loop, allowing lower distribution temperatures (and therefore lower thermal losses) and reducing connection risk through a “plug and play” approach.

DHN research in the past has largely focused on methods to reduce the supply temperature for 4th generation (4G) applications. Østergaard and Lund [20] present a proposal and technical method for Frederikshavn (Denmark) to become a 100% renewable city, utilising low temperature geothermal energy in a DHN. Gadd and Werner [21] analyse low temperature substations for fault detection. Østergaard and Svendsen [22] define the need to replace critical heat emitters in secondary distribution, Best and Orozaliev [23] suggest an economic benefit to “ultra low temperature” networks over low temperature networks.

In more recent years, the research focus has moved away from reducing the supply temperature and towards smart energy networks. A key part of smart energy networks is demand side management (DSM). Cai, Ziras [24] provide mathematical modelling to optimise heating demand response on a CHP heat network. Wang, Hu [25] create a CHP dispatch optimisation based on retail energy markets, and Saletti, Zimmerman [26] propose to optimally manage the state of charge in heat networks for peak reduction in a CHP network. Many of these studies have focused exclusively on using CHP. It is expected that the uptake of CHP will be greatly reduced in future due to the challenge in decarbonizing these systems.

The reduction in supply temperature and inclusion of smart demand side management has allowed waste heat recovery to be considered in more detail. Bühler, Petrović [27] evaluates through spatial analysis the potential for waste heat to be used in DHNs. Broberg, Backlund [28] studies the untapped potential for industrial excess heat in Sweden. Weinberger, Amiri [29] show the economic and environmental benefits of heat recovery for a case study in Sweden. Much of the current literature on waste heat recovery focuses on one waste heat source (e.g. data centre, CHP exhaust) being delivered through the main heat network to the end users. However, there is also scope for decentralised prosumer thermal energy sharing as well.

There have been several terms coined for thermal energy sharing networks; examples include “Cold District Heating Networks” [30], “Bidirectional low temperature networks” [31], and “Peer to Peer Network” [32]. Each definition has subtle differences, which has caused some disparity within literature. For the purpose of this study, we describe a thermal energy sharing network as a “5th generation district heating and cooling network”. We give details of what we have included in our definition, below.

5.1.1. 5th Generation District Heating and Cooling

For the purpose of this study, we define a 5th Generation District Heating and Cooling Network (5GDHCN) as having the following key points:

- A significant number of end users capable of prosuming heat and coolth

- Energy is distributed via a low (ambient) temperature distribution loop

- Low grade thermal sources used to buffer the ambient loop.

Additionally, many proposed 5GDHCNs will utilise a decentralised pool of two-directional heat pumps which can provide both heating and cooling to the end user. This is largely in accordance with the definition provided by Boesten, Ivens [33]. It is acknowledged that this definition is flexible and evolving, but for the purpose of this study we use this definition.

Bünning, Wetter [31] discuss the concept of operational control in 5GDHCNs, using dynamic modelling based on a set temperature in the distribution loop. The case study is used to test performance of the novel control algorithm, but limited discussion is given around the importance of the energy sharing demand profiles. Revesz, Jones [34] give a detailed techno-economic and feasibility study for a case study in London, UK. The study focuses primarily on the case study, and offers useful insights, but uses a limited and less common combination of demand profiles. Similarly, Murphy and Fung [35] present a techno-economic case for energy sharing between a data centre and a single apartment block. In principle, this case is a 5GDHCN but as the scheme is fairly small, is excluded from our definition. In the future, this may be classes as a “5th generation communal district heating and cooling network" as the modern equivalent of 3rd generation communal networks. Boesten, Ivens [33] describe an energy sharing network for the case study of the Mijnwater system in Heerlen. The contribution discusses the definition of 5GDHCNs but does not give any technical insight to the performance drivers of these networks.

To our knowledge, there are currently no wide-scale applications of these systems. However small systems are both in operation and under construction. One of the first in the UK is present at the London South Bank university, which uses a cold water network to exchange heat between two tower blocks and is supported by aquifer thermal abstraction [36]. This is an example of an integrated system which uses thermal storage, smart demand side response and time of use tariffs to minimise the effect electrification of heat can have on the national electrical grid. This example showcases the key requirements of a 5G heat network but is unclear how this model could be replicated in more diverse end user groups or with a different asset owner. Until now, DHNs have been a purely consumer driven market, with heat flows in one direction from the energy centre to the consumer. This is the sensible solution when the heat source is from chemical conversion (e.g. natural gas or biomass), but if an electrified heating market is established, heat pumps become the sensible option. When using heat pumps in heating mode, heat is abstracted from a lower temperature source (e.g. air, ground, rivers), making the source colder. This produces offset coolth which could be used to meet the cooling load of another building. This would require the energy sharing buildings to be hydraulically connected through a heat network. If the temperature of this network is kept low (circa 20-40°C) then a 2-pipe system could be used with a heat pump to provide either heating or cooling, removing the need for a 4-pipe system, while reducing thermal losses dramatically when compared to 3G networks. However, as the temperature is so low, each building or subnetwork will require its own heat pump to boost the network energy carrier to the required temperature.

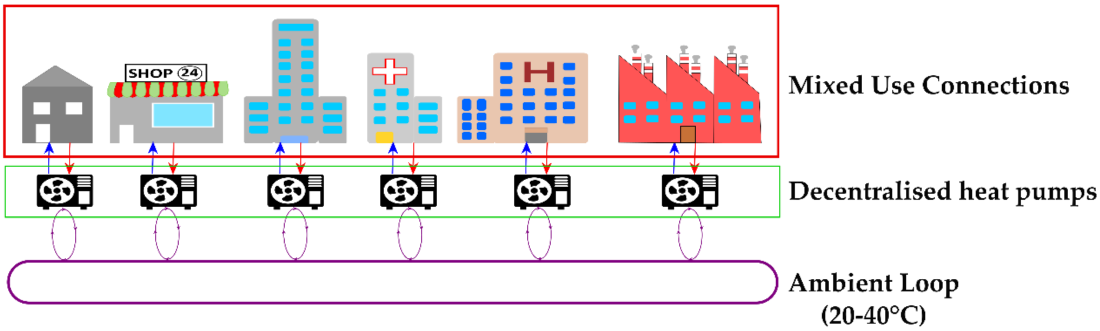


Figure 5-1 Schematic of potential 5th Generation Heat Network with mixed end users with different load profiles, a group of decentralised heat pumps all connected hydraulically via low temperature, "ambient", network.

Although 5G DHNs are being encouraged via government supported trials, it is unclear of the technical or economic feasibility of these systems for larger applications. This will have significant implications for investors and will make uptake unlikely due to the uncertainty.

5.1.2. *Novel Contributions*

Previous studies have evaluated very small scale thermal energy sharing (i.e. no more than two energy sharers) [35, 36] with a very limited number of thermal demand profiles; typically residential buildings, and others have considered commercial sub-let space as a microgrid [37].

The current literature has considered the implications the of electrification of heat may have; some studies have focused on managing the end user electricity demand [38], other studies have presented a top-down model of electricity network interactions [39], and further works have propose power to heat scenarios during curtailment periods [40]. While these studies have importance in energy sharing, they do not discuss in detail true thermal energy sharing via hydraulic connection. There are currently no studies which evaluate the benefit of 5GDHCNs over traditional networks, and there are no studies which evaluate the key drivers to a successful energy sharing network.

It is proposed that this paper will address the knowledge gaps discussed above. The paper presents a detailed analysis of complementary heating and cooling loads that implies which building types may be well suited to thermal energy sharing; this has not been addressed in literature prior to now.

The findings are presented with comparison to traditional heat networks and assess the economic and carbon benefits of each case. This is achieved through a multi-objective Mixed Integer Linear Programming (MILP) optimisation dispatch problem, where the objective is to minimise both capital investment and operating cost, which is similar to the methodology proposed by Akter, Mahmud [41]. We produce heating and cooling load profiles from Integrated Environmental Solutions Virtual Environment (IES VE) for a busy, mixed use street in the UK. This is used as a basis for equipment selection, including heat pump capacity and Thermal Energy Storage (TES) capacity.

The contributions of this paper are therefore to:

- Propose a framework for assessing the economic feasibility of 5th generation energy sharing networks
- Provide a comparative analysis of technical metrics between traditional networks and energy sharing networks.
- Identify the significance of tariff structure on an energy sharing network design and demand response strategy.
- Identify the importance of key design metrics on the ability to share thermal energy between buildings
- Identify the economic and technical benefit energy sharing networks may have
- Assess the compatibility of different building usages to offer complimentary heating and cooling loads

5.1.3. Paper structure

The remainder of the paper is organised as follows. Section 2 describes the mathematical modelling and optimisation framework. Section 3 gives the metrics used for comparison between scenarios. Section 4 gives details on the case study used. Section 5 is the results and discussion. Section 6 gives the limitations of the study. Section 7 is the conclusions, and Section 8 gives the proposed future work.

5.2. System Description

In a perfect 5G heat network, all of the shared heating and cooling would be utilised. This is not possible due to system losses, response time and load matching challenges. The system is designed that each user has a heat pump which can operate either in heating mode or in cooling mode, supported (when necessary) by large scale energy source (e.g. ground source, mine water). For this study, heating is inclusive of domestic hot water (DHW) (e.g. Total heat demand is space heating plus DHW). The system is modelled from a network operator perspective, with one aggregate hot-side demand and one cold-side demand for the network to respond to. In practice, this could be multiple end user heat pumps or heat pumps in distributed substations; for our study we assume the aggregate demand is equivalent regardless of the heat network distribution choice.

The hot-side heat pump abstracts energy from the ambient loop and will upgrade this to a higher-grade heat using electricity. This heat can either be utilised immediately by the demand, or it can be stored for later use. As the heat pump produces heat, it will also produce coolth from the evaporator which can be shared via the ambient loop. This coolth can either be used immediately to meet the cold-side demand, can be stored for future use or can be wasted.

The cold side heat pump rejects heat to the ambient loop, absorbing coolth, to provide a cooling effect using electricity. In a similar manner to how the heat is used in the hot-side, coolth can either be sent direct to demand or stored for later use. As the cold-side heat pump produces coolth, it will also produce heat from the condenser which can be shared via the ambient loop. The heat can either be used immediately to meet the hot-side demand, can be stored for later use or can be wasted.

It is anticipated that the smart management of loads and energy sharing will keep the ambient loop temperature approximately constant, allowing the utilisation of low grade energy sharing. This is summarised diagrammatically by Figure 5.2.

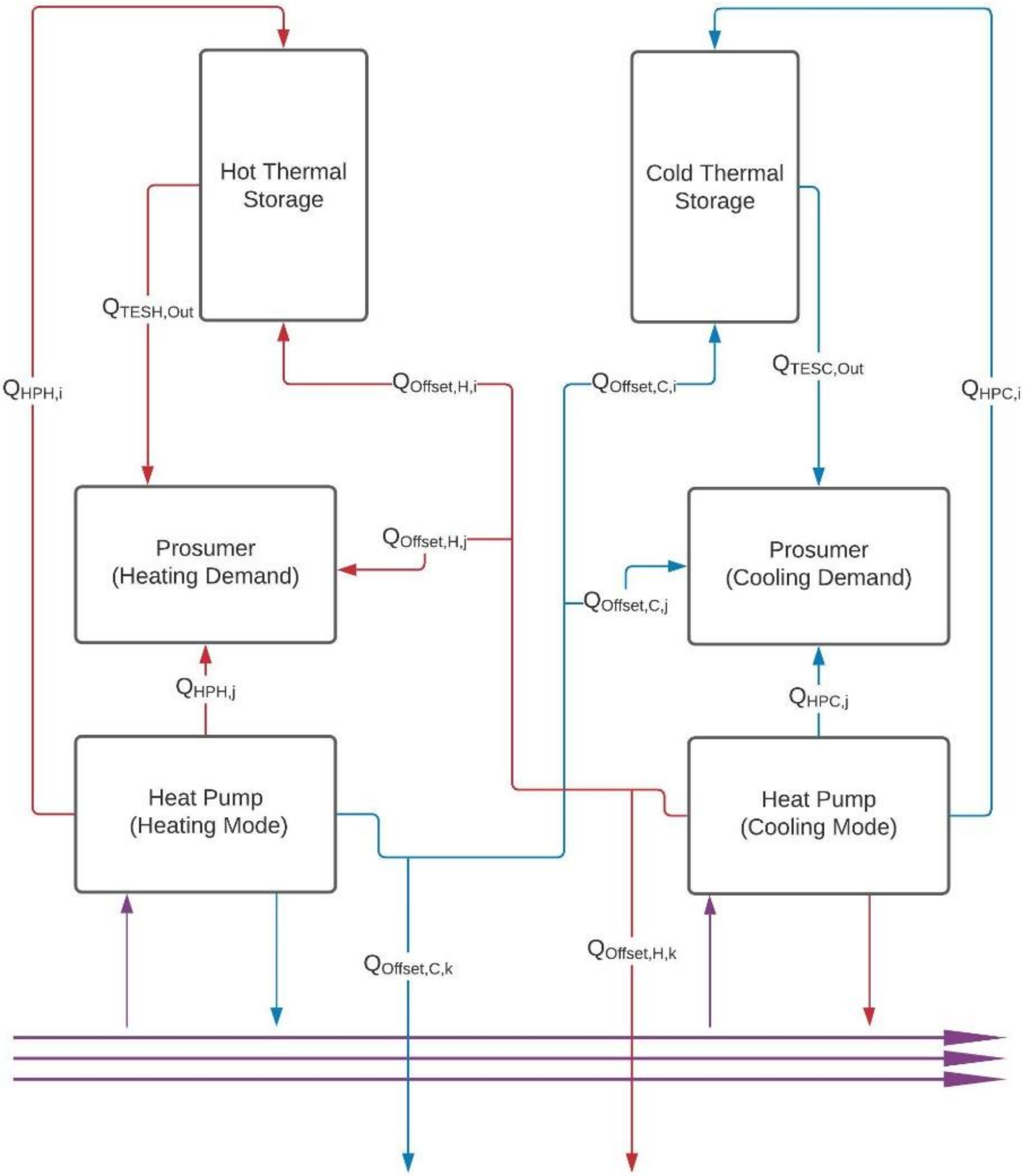


Figure 5-2 Block diagram of modelled 5G DHN. Each prosumer can abstract or reject energy to the network, and is able to share with other prosumers connected to the network.

5.2.1. Optimisation Framework

The objective of the optimisation is to maximise the Net Present Value (NPV) . This is achieved using a mixed-integer linear programming (MILP) problem which, designed to select the most cost effective combination of heat pump capacity, TES and heat pump operating profile that can be used to meet the demand. The objective function becomes Equation 1, where $\boldsymbol{C^{inv}}$ is the investment cost, $\boldsymbol{C^{opr}}$ is the operating cost, r is the discount rate (8%) and n is the life of the project, 25 years. C^{rev} is the revenue from heat and coolth sales at £0.04/kWh to be comparable with alternative systems in the UK (i.e. natural gas). It is assumed that the revenue will rise at the same rate of escalation as the operating cost, set at 0.2% per year.

$$\mathbf{max} \quad \mathbf{NPV} = \mathbf{max}\left\{\sum_{n=0}^{25} \frac{C^{rev} - C^{opr}}{(1+r)^{n}} - C^{inv}\right\} \qquad [1]$$

The investment cost is the sum of all initial capital expenditure (n=0), shown in Equation 2.

$$\begin{aligned} C^{inv} &= C^{inv}_{HPH} + C^{inv}_{TESH} + C^{inv}_{HPC} + C^{inv}_{TESC} \\ &= C^{inv}_{HP,kw}\left(Q_{HPH,max} + Q_{HPC,max}\right) \\ &\quad + C^{inv}_{TES,kw}\left(Q_{TESH,max} + Q_{TESC,max}\right) \end{aligned} \qquad [2]$$

where C^{inv}_{HPH} and C^{inv}_{TESH} is the investment cost of the heat-led heat pump and hot side TES respectively. C^{inv}_{HPC} and C^{inv}_{TESC} are the investment cost of the coolth-led heat pump and cold side TES. The investment costs are based on maximum capacities, $Q_{HPH,max}$, $Q_{TESH,max}$, $Q_{HPC,max}$, and $Q_{TESC,max}$ are the installed capacity of the heat-led heat pump, hot side TES, coolth-led heat pump and cold side TES, respectively. The program is formulated as a discrete binary integer problem such that:

$$\mathbf{Q_{HPH,max}} = \sum \mathbf{Q_{HPH,n}} \cdot \mathbf{Q_{HPH,max,cap}} \qquad [3]$$

$$\mathbf{Q_{TESH,max}} = \sum \mathbf{Q_{TESH,n}} \cdot \mathbf{Q_{TESH,max,cap}} \qquad [4]$$

$$\mathbf{Q_{HPC,max}} = \sum \mathbf{Q_{HPC,n}} \cdot \mathbf{Q_{HPC,max,cap}} \quad [5]$$

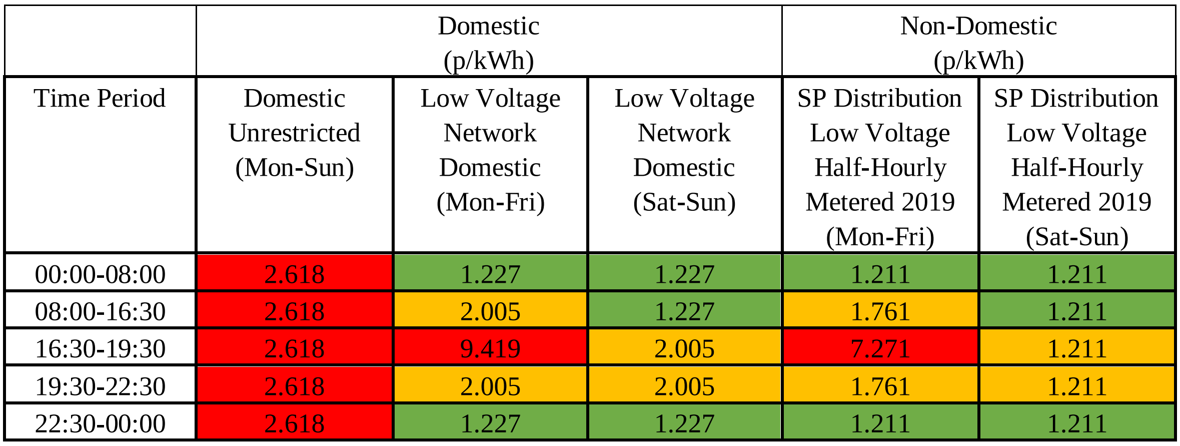
$$\mathbf{Q_{TESC,max}} = \sum \mathbf{Q_{TESC,n}} \cdot \mathbf{Q_{TESC,max,cap}} \quad [6]$$

$\boldsymbol{Q_{HPH,n}}$is a binary decision vector of equal magnitude to $\boldsymbol{Q_{HPH,max,cap}}$. The decision vector can take an integer value of either 0 or 1 in each place holder but must sum to 1, so that only one capacity per piece of equipment is selected. The optimisation algorithm will place a 1 in the position which correlates to the chosen equipment size.
$\boldsymbol{Q_{TESH,n}}$, $\boldsymbol{Q_{HPC,n}}$ and $\boldsymbol{Q_{TESC,n}}$ are similar binary decision variables for the hot-side TES, the cold-side heat pump and the cold-side TES respectively.

The operating cost is the electricity used by the heat pumps multiplied by the unit cost per kWh of electricity, $\boldsymbol{C_{el}}$, shown in Equation 7. This is taken from the Scottish Power charging statement for unrestricted domestic users, shown in Table 1. This is effectively a wholesale price and not the price the end user would pay. This is used to remove ambiguity around electrical tariffs which will vary from user to user. COP_H and COP_C are the Coefficient of Performance (COP) for the hot side and cold side heat pumps, chosen as 3 for both. The performance of hot and cold side heat pump is chosen to be the same to offer a cleaner comparison in the absence of detailed information on the modelled building internal distribution equipment.

$$\mathbf{C^{opr}} = \boldsymbol{C_{el}} \times \left(\frac{\boldsymbol{Q_{HPH,out}}}{\boldsymbol{COP_H}} + \frac{\boldsymbol{Q_{HPC,out}}}{\boldsymbol{COP_C}} \right) \quad [7]$$

Table 5.1 Tarriff structure for electrical costs based on the Scottish Power Charging statement. Showing high cost (red), medium cost(orange) and low cost (green) periods. Domestic Unrestricted is shown as high cost as this tariff would typically lead to the largest cost per year. 1p is equal to £0.01GBP



	Domestic (p/kWh)			Non-Domestic (p/kWh)	
Time Period	Domestic Unrestricted (Mon-Sun)	Low Voltage Network Domestic (Mon-Fri)	Low Voltage Network Domestic (Sat-Sun)	SP Distribution Low Voltage Half-Hourly Metered 2019 (Mon-Fri)	SP Distribution Low Voltage Half-Hourly Metered 2019 (Sat-Sun)
00:00-08:00	2.618	1.227	1.227	1.211	1.211
08:00-16:30	2.618	2.005	1.227	1.761	1.211
16:30-19:30	2.618	9.419	2.005	7.271	1.211
19:30-22:30	2.618	2.005	2.005	1.761	1.211
22:30-00:00	2.618	1.227	1.227	1.211	1.211

The total operating costs are calculated as the cost of electricity at time period, $C_{el,t}$, multiplied by the units of power consumed at that time interval, $P_{HP,in,t}$,shown in Equation 8.

$$C^{opr} = \sum_{t=0}^{t=8759} P_{HP,in,t} \times \left(\frac{C_{el,t}}{COP_H} + \frac{C_{el,t}}{COP_C}\right) \qquad [8]$$

5.2.2. *Energy Balance*

On the hot side, the demand is made of heat provided directly from the heat pump in heating mode, $Q_{HPH,j}$, shared heat from the heat pump in cooling mode, $Q_{offset,H,j}$ and heat from the hot side TES, $Q_{TESH,out}$, summarised in Equation 9.

$$Q_{dem,h} = Q_{HPH,j} + Q_{TESH,out} + Q_{offset,H,j} \qquad [9]$$

The heat pump uses electricity in the form of work energy to upgrade a low-grade thermal resource to a higher-grade resource. This is the heat produced from the heat pump, $Q_{HPH,out}$, and can either be stored in the hot side TES, $Q_{HPH,i}$, or can be used directly to meet the demand, $Q_{HPH,j}$, shown in Equation 10.

$$\mathbf{Q_{HPH,out} = Q_{HPH,i} + Q_{HPH,j}} \quad [10]$$

Equivalent equations for the cold side are shown in Equation 11 and 12.

$$\mathbf{Q_{dem,c} = Q_{HPC,j} + Q_{TESC,out} + Q_{offset,C,j}} \quad [11]$$

$$\mathbf{Q_{HPC,out} = Q_{HPC,i} + Q_{HPC,j}} \quad [12]$$

For the hot side, the shared energy, $\boldsymbol{Q_{offset,H}}$, can be stored, $\boldsymbol{Q_{offset,H,i}}$, used directly to meet demand, $\boldsymbol{Q_{offset,H,j}}$, or can be wasted to the environment, $\boldsymbol{Q_{offset,H,k}}$, shown in Equation 13. The equivalent cold side is shown in Equation 14.

$$\mathbf{Q_{offset,H} = Q_{offset,H,i} + Q_{offset,H,j} + Q_{offset,H,k}} \quad [13]$$

$$\mathbf{Q_{offset,C} = Q_{offset,C,i} + Q_{offset,C,j} + Q_{offset,C,k}} \quad [14]$$

There is a hot and cold TES. The energy balance around the hot TES is shown in Equation 15.

$$\mathbf{Q_{TESH,t} = Q_{TESH,t-1} + Q_{HPH,i} + Q_{offset,H,i} - Q_{TESH,out}} \quad [15]$$

$\boldsymbol{Q_{TESH,t}}$ is the hot-side energy stored in the hot side TES at time, t. $\boldsymbol{Q_{TESH,t-1}}$ is the hot-side energy stored in the TES at the previous time step. The cold side is shown in Equation 16.

$$\mathbf{Q_{TESC,t} = Q_{TESC,t-1} + Q_{HPC,i} + Q_{offset,C,i} - Q_{TESC,out}} \qquad [16]$$

The amount of energy that has the potential be shared is based on the energy balance of a heat pump, shown in Equation 17 and 18.

$$\mathbf{Q_{offset,H} = Q_{HPC,out} + \frac{Q_{HPC,out}}{COP_C}} \qquad [17]$$

$$\mathbf{Q_{offset,C} = Q_{HPH,out} - \frac{Q_{HPH,out}}{COP_H}} \qquad [18]$$

5.2.3. Carbon based optimisation framework

The overarching goal of implementing renewable and low carbon technology is to minimise carbon emissions; however, this can come at the expense of choosing the most cost-effective option. The aim of the carbon analysis presented is to assess the deviation in financial cost between the most cost effective and being the lowest carbon option. The variables and constraints on the optimisation are the same as the cost-based optimisation, however the optimisation function is updated to reflect the “carbon cost”, or carbon intensity, per hour of electricity from the UK national grid. The carbon intensity will vary due to the changing share of renewables in the mix. A sample day is given in Figure 5.3.

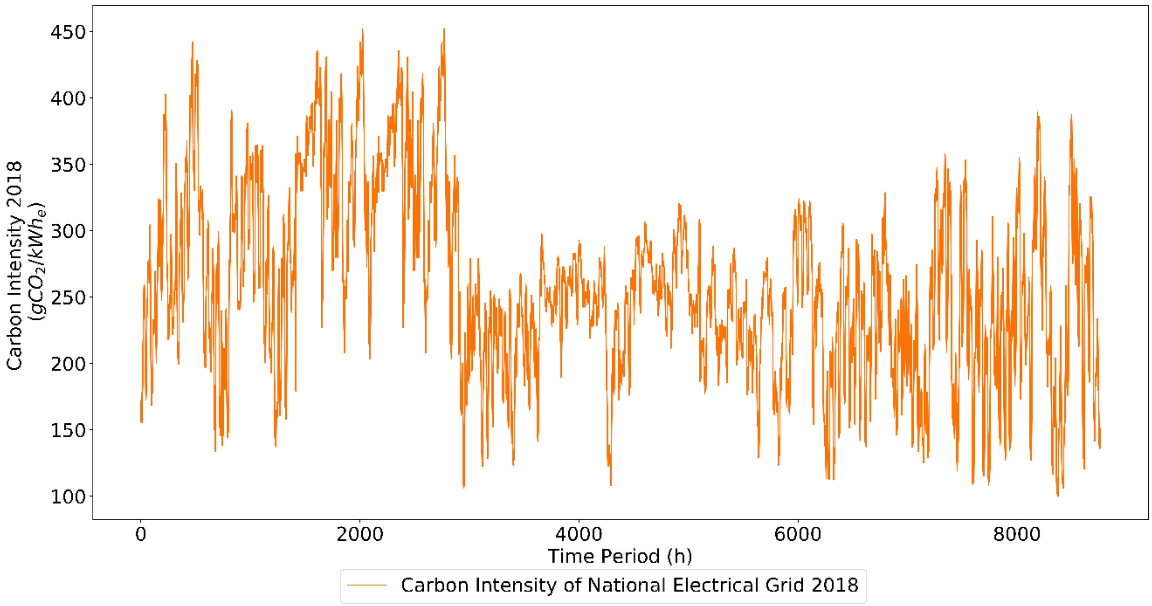


Figure 5-3 Typical carbon intensity across a sample day for the UK electrical grid, taking from the National Statistics Database.

The cost of carbon can be defined by the carbon EU Allowance (EUA). This is around £25/ tonne CO_2 emitted. The impact of a carbon-based tariff on energy sharing is assessed by introducing a carbon-cost to the objective function, shown in Equation 19.

The objective function for the carbon-based optimisation becomes Equation 19.

$$\mathbf{max} \quad \mathbf{NPV} = \mathbf{max}\left\{\sum_{\mathbf{n=0}}^{\mathbf{25}} \frac{\mathbf{C^{rev}} - (\mathbf{C^{opr}} + \mathbf{C_{tot}^{CO_2}})}{(\mathbf{1+r})^{\mathbf{n}}} - \mathbf{C^{inv}}\right\} \tag{19}$$

$C_{tot}^{CO_2}$ is the total carbon cost across the life of the project and EUA is the cost of carbon in £/tonne carbon. This is shown in Equation 20.

$$\mathbf{C_{tot}^{CO_2}} = \sum_{n=0}^{n=25} \sum_{t=0}^{t=8759} \mathbf{P_{HP,in,t}} \times \mathbf{C^{CO_2}} \times \mathbf{EUA} \qquad [20]$$

C^{CO_2} is the carbon intensity of the electrical grid at time period, t. To our knowledge, an hourly carbon intensity forecast is not available for the next 25 years. Instead, a sample historical year data normalised against the average for that year is used. Hourly profiles are then produced from the forecast yearly average for the next 25 years.

5.3. Analysis metrics

There are a number of metrics which can be used to assess the benefit provided from energy sharing. In this study, these are divided into technical, economic or environmental.

5.3.1. Technical Metrics

The technical metrics are chosen as simple indicators of performance. These metrics show benefit for the distribution network, the electrical grid, or as an aid for decision making around network topology.

5.3.1.1. Diversity Factor

When distributed energy networks are not used (e.g. each user has a gas boiler/air conditioning), the peak load on the energy system is the peak of the individual user. In a distributed system, it can be incorrectly assumed that the peak load on the network is the sum of the peak demand of each individual user connected to the network. In practice, it is unlikely that all users connected to a network will have a peak demand simultaneously. The occupancy of a space can vary drastically and therefore the Domestic Hot Water (DHW) demand. The probability of coincident peak loads is known as “diversity”. Space conditioning is much more likely to be coincident and therefore diversity factor is not typically applied to this. The diversity factor is defined in Equation 21.

$$Diversity\ \ Factor = \frac{Q_{EC}}{\sum Q_{peak}} \tag{21}$$

$\boldsymbol{Q_{EC}}$ is the peak energy provided from the energy centre or production plant and Qpeak is the peak energy demand of an end-user. The diversity factor of the hot and cold side heat pumps can be calculated from Equation 22 and 23.

$$Hot\ \ Side\ \ Diversity = \frac{Q_{HPH,max}}{Q_{peak,h}} \tag{22}$$

$$Cold\ \ Side\ \ Diversity = \frac{Q_{HPC,max}}{Q_{peak,c}} \tag{23}$$

A lower diversity factor implies a greater diversity. A greater diversity will place reduced strain on the national grid electrical network when coping with mass electrification of heat/cooling. The increased diversity will reduce the installed capacity of production equipment and distribution infrastructure, and therefore reduce costs. A greater diversity encourages production equipment to operate at peak installed capacity for greater duration; this operating style will increase the overall COP of the heat pump network.

5.3.1.2. Floor Normalised Loads

From the case study presented, it is possible to extract floor normalised load profiles from the IES VE calculated heating and cooling loads. This can be used to select a priority order of building classes for energy sharing. The floor normalised loads for a range of scenarios are fed to the optimisation algorithm which is arranged to produce the best cost-case utilisation of shared heat. This is presented for four key building types – office, retail, hotel and residential, as a guide to which building topologies are inherently better suited to energy sharing. This relies on energy loads in buildings being modular – the heating load can be separated from the cooling load. This offers a greater degree of freedom with a much larger range of heating and cooling load combinations. This is presented as the percentage of potential shared energy which is wasted.

5.4. Economic Metrics

The Levelised Cost of Energy (LCOE) can be used along with the NPV to assess the economic incentive of energy sharing. LCOE provides a measure of the average net present cost of generating heat or coolth across the lifecycle of the scheme, shown in Equation 24. It is the revenue per kWh of energy which must be recouped to cover the costs used in the assessment.

$$\mathrm{LCOE} \ = \mathbf{C}^{\mathbf{inv}} + \sum_{\boldsymbol{n}=\mathbf{0}}^{\mathbf{25}} \frac{\sum_{\boldsymbol{t}=\mathbf{0}}^{\boldsymbol{t}=\mathbf{8759}} \frac{\mathbf{C}^{\mathbf{opr}}}{(\mathbf{1}+\boldsymbol{r})^{\boldsymbol{n}}}}{\frac{\boldsymbol{Q}_{\boldsymbol{dem,h}} + \boldsymbol{Q}_{\boldsymbol{dem,c}}}{(\mathbf{1}+\boldsymbol{r})^{\boldsymbol{n}}}} \tag{24}$$

For the scenarios with carbon tax (EUA), the LCOE becomes Equation 25.

$$\mathrm{LCOE} \ = \mathbf{C}^{\mathbf{inv}} + \sum_{\boldsymbol{n}=\mathbf{0}}^{\mathbf{25}} \frac{\sum_{\boldsymbol{t}=\mathbf{0}}^{\boldsymbol{t}=\mathbf{8759}} \frac{\mathbf{C}^{\mathbf{opr}} + \boldsymbol{C}_{\boldsymbol{tot}}^{\boldsymbol{CO}_{\mathbf{2}}}}{(\mathbf{1}+\boldsymbol{r})^{\boldsymbol{n}}}}{\frac{\boldsymbol{Q}_{\boldsymbol{dem,h}} + \boldsymbol{Q}_{\boldsymbol{dem,c}}}{(\mathbf{1}+\boldsymbol{r})^{\boldsymbol{n}}}} \tag{25}$$

This LCOE calculation only accounts for the capital investment and operating profile chosen by the optimisation algorithm. It does not account for additional overheads, such as staff costs of operating the network, maintenance etc. The total energy consumed remains the same across all scenarios. The LCOE will provide a metric to compare the optimised operating profile for each scenario.

5.5. Heating and Cooling Profiles – A case study

Heat networks work best in high population density areas but an additional requirement for 5G DHNs is that there is a constant baseload of heating and cooling demand. The baseload heat could be from DHW and the constant cooling could be from supermarket refrigerators; however due to the challenges in providing de-centralised refrigerator cooling, this is excluded from this study. In order to demonstrate the proposed framework for system optimisation, a city-centre street in the UK is chosen for a case study, which is the Glasgow Queen Street (centred on 55.8625°N, 4.2512°W). In real terms, this could be an ideal location due to the high heating and cooling demand, with mixed use buildings. The network length is approximately 322m (0.2 miles).

The energy demands are produced from Integrated Environmental Solutions Virtual Environment (IES VE), a thermal simulation tool, using typical weather file for Glasgow. The IES VE modelling approach is documented in detail elsewhere, and therefore only provided in light detail below [13].

A 3D model of the street is first produced in IES VE. Assumptions around the building constructions are made based on visual inspection and the year of construction. Historic thermal properties are taken from Appendix S of RdSAP 2012, the standard assessment procedure for existing dwellings in the UK [42].

The key driving factors of building energy usage are the building fabric, internal gains, and the external air temperature. For the purpose of modelling, the street is grouped into building usage types shown in Table 2. From literature and experience, indicative values of occupancy, lighting, and small power gains are chosen. These are connected with sensible usage profiles, shown in.

5.6. Modelling Approach

The heating and cooling demand will vary depending on the external air temperature, building fabric (e.g. conductivity, air exchanges), and internal gains. These are summarised in Table 2 and Figure 5.4. Standard values are used for the equipment and lighting gains. The occupancy gains are dependant on the activity of the space and therefore has variation across building uses (e.g. a person doing heavy labour will sweat more and therefore contribute greater latent gain to the space).

Table 5.2 Summary of the internal gains per building class used in demand modelling. The profiles are created using best practice guides, experience, and common sense.

Internal Gain Type		Dining – Bar/Lounge	Dining – Cafeteria/Fast Food	Dining – Family	Hotel	Dwelling	Museum	Office	Retail	Warehouse
Equipment	Maximum Sensible Gain (W/m^2)	1.076	1.076	1.076	60	15	2.69	16	2.69	1.08
Lighting	Maximum Sensible Gain (W/m^2)	10.872	9.688	9.688	15	15	10.98	12	13.56	7.1
Occupancy	Maximum Sensible Gain (W/m^2)	80	80	80	73	73	73	73	73	186
	Maximum Latent Gain (W/m^2)	80	80	80	58	58	58	58	58	282
	Occupancy density (m^2/person)	9.29	9.2	9.2	23	23	27	25	27	30
DHW	l/hour.person	1	1	1	16	5	1	0.625	1	0.5

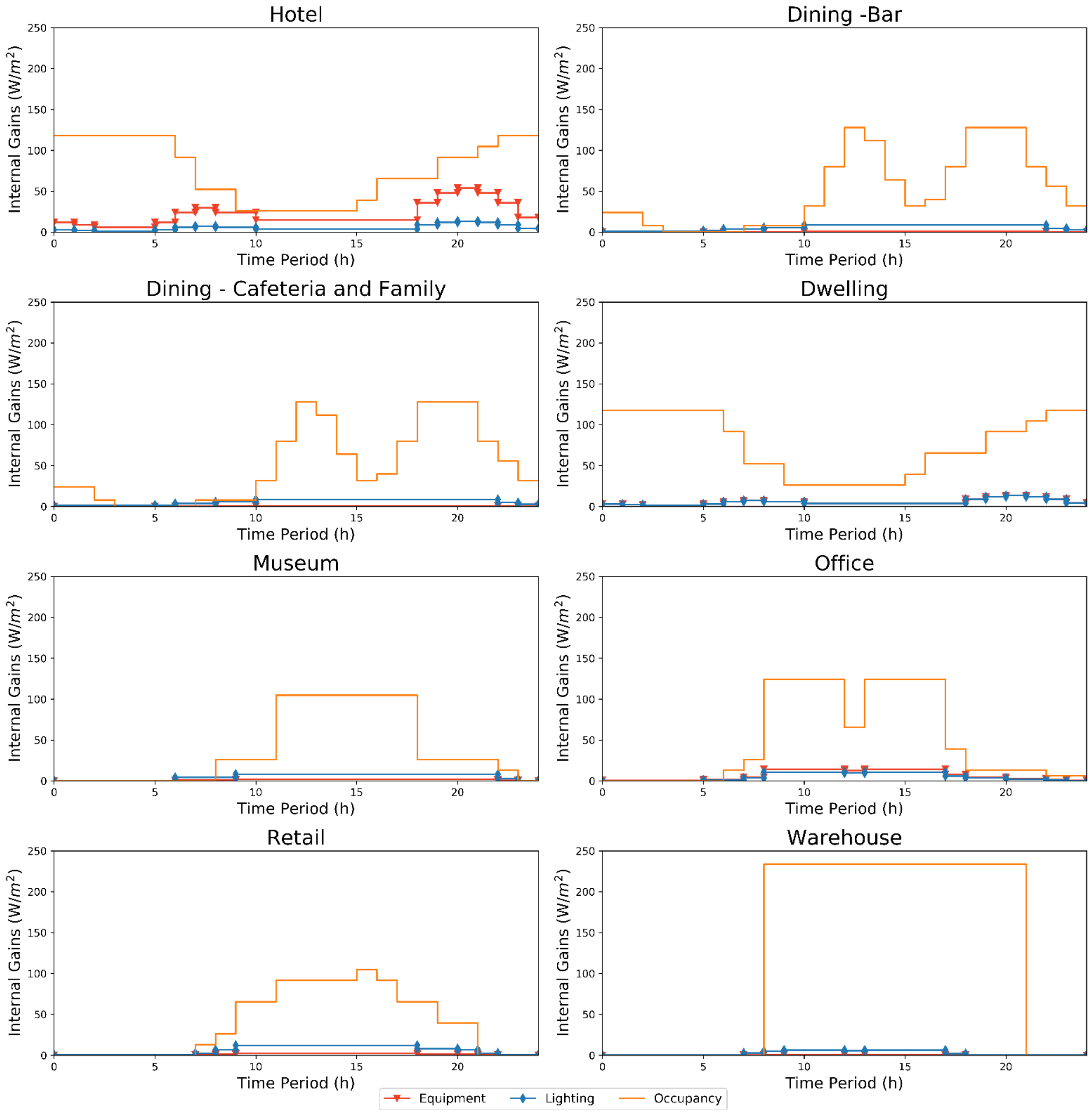


Figure 5-4 Daily variation in internal gains, shown in watts per square metre. The occupancy gain profiles are not divided by activity groups (e.g. bedroom, kitchen etc.).

A summary of the energy loads for each building type is provided in Table 3 and the 3D model is presented in Figure 5.5.

Table 5.3 Summary of Building Types and corresponding heating, cooling, and domestic hot water demand for the modelled building types

Building Type	Floor Area (m^2)	Heating Demand (MWh)	Domestic Hot Water (MWh)	Cooling Demand (MWh)
Dining – Bar/Lounge	249	22.9	4	0.47
Dining – Cafeteria/Fast Food	884	70.6	14.2	2.23
Dining – Family	911	67.1	14.6	2.7
Hotel	8’672	320.6	1171	19.7
Dwelling	6’557	245	276.8	0
Museum	6’927	476	37.6	1.8
Office	43’576	1’338	259	409.31

Retail	50’667	944.5	349.5	1’205
Warehouse	7’368	439.6	0	0
Total	125’811	3’925.98	2’127.7	1541

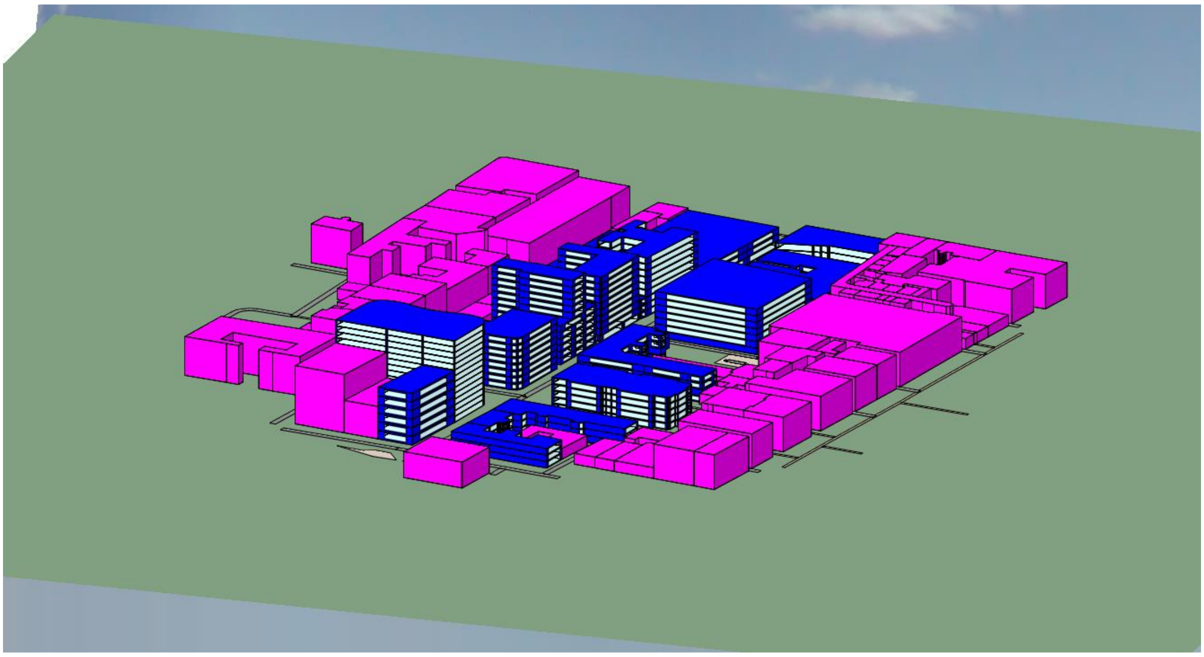


Figure 5-5 3D model of the presented case study. Blue buildings show modelled zones and pink shows shading objects.

Figure 5.6 shows the simulated aggregate heating and hot water and cooling load for the sample study. The cooling load is much smaller than the heating load. The peak heating demand is 7.2MW and the peak cooling demand is 3.4MW.

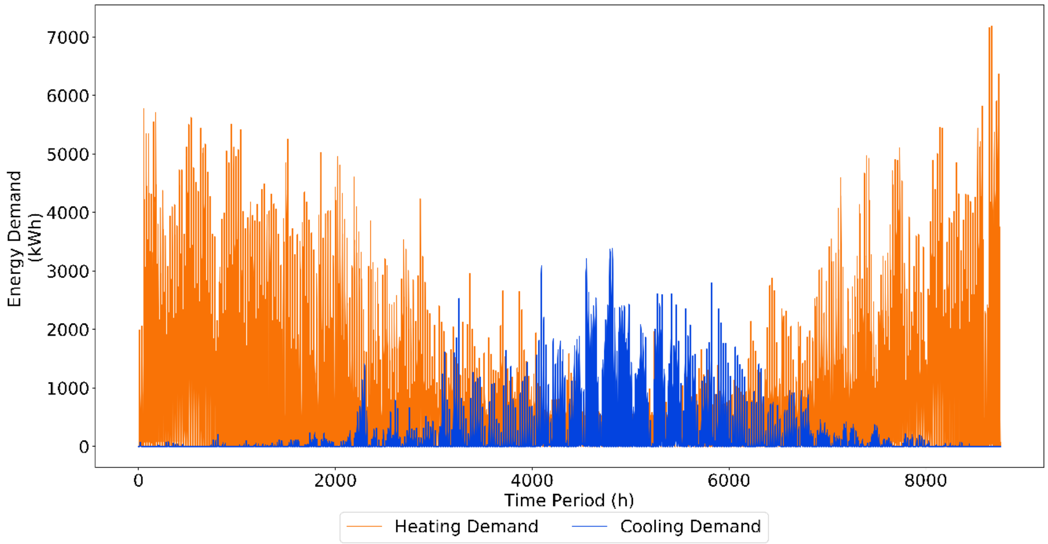


Figure 5-6 Simulated total Heating and Cooling loads for the sample stud showing significant seasonal variation in heating (orange) and cooling demand (blue)

5.6.1. Case Study Scenarios

Sixteen distinct scenarios were considered with the case study to assess the influence of demand side management (DSM) and energy sharing on the techno-economic feasibility of the system. These are summarised in Table 4 and Table 5.

Table 5.4 Description of scenario variable used; tariff, energy sharing, thermal storage, and carbon taxation.

	Scenario Variable	Description
Tariff	Fixed Rate	Electricity is charged at one rate
	Tout	Electricity cost varies across the day/week. Lower rates are given for off-peak periods
Energy Sharing	With Share	Offset energy can be shared through the network
	No Share	No energy can be shared (becomes 4th generation network)
Thermal Storage	With Store	Energy storage can be utilised (hot and cold)
	No Store	No energy can be stored
Carbon Tax	With Carbon	A carbon levy is added based on the national grid carbon factor
	No Carbon	No carbon levy is added

Table 5.5 Summary of tested scenarios showing the tariff, energy sharing, thermal storage, and carbon tax combinations assessed.

Scenario Number	Tariff	Energy Sharing	Thermal Storage	Carbon Tax
1	Fixed Rate	No Store	With Share	No carbon
2	Fixed Rate	No Store	With Share	With carbon
3	Fixed Rate	No Store	No Share	No carbon
4	Fixed Rate	No Store	No Share	With carbon
5	Fixed Rate	With Store	With Share	No carbon
6	Fixed Rate	With Store	With Share	With carbon
7	Fixed Rate	With Store	No Share	No carbon
8	Fixed Rate	With Store	No Share	With carbon
9	TOUT	No Store	With Share	No carbon
10	TOUT	No Store	With Share	With carbon
11	TOUT	No Store	No Share	No carbon
12	TOUT	No Store	No Share	With carbon
13	TOUT	With Store	With Share	No carbon
14	TOUT	With Store	With Share	With carbon
15	TOUT	With Store	No Share	No carbon
16	TOUT	With Store	No Share	With carbon

5.7. Results and Discussion

Energy sharing networks are novel technology and not found extensively anywhere. The discussion presented in this section makes some assumptions around the business model and structure which is necessary to understand and reason the results and conclusions.

The following statements are assumed for the discussion:

- The network customer is charged for the heat, cooling, and hot water from the network operator as one charge based on the energy absorbed from the network (ie no distinction is made with regards to the grade of heat absorbed)

- no compensation is provided for energy rejected to the ambient loop

- the network operator and/or owner are responsible for the capital investment cost. In this scenario, all financial metrics are from the network owner/operator, who in practice may be the same entity.

A summary is given in Figure 5.7.

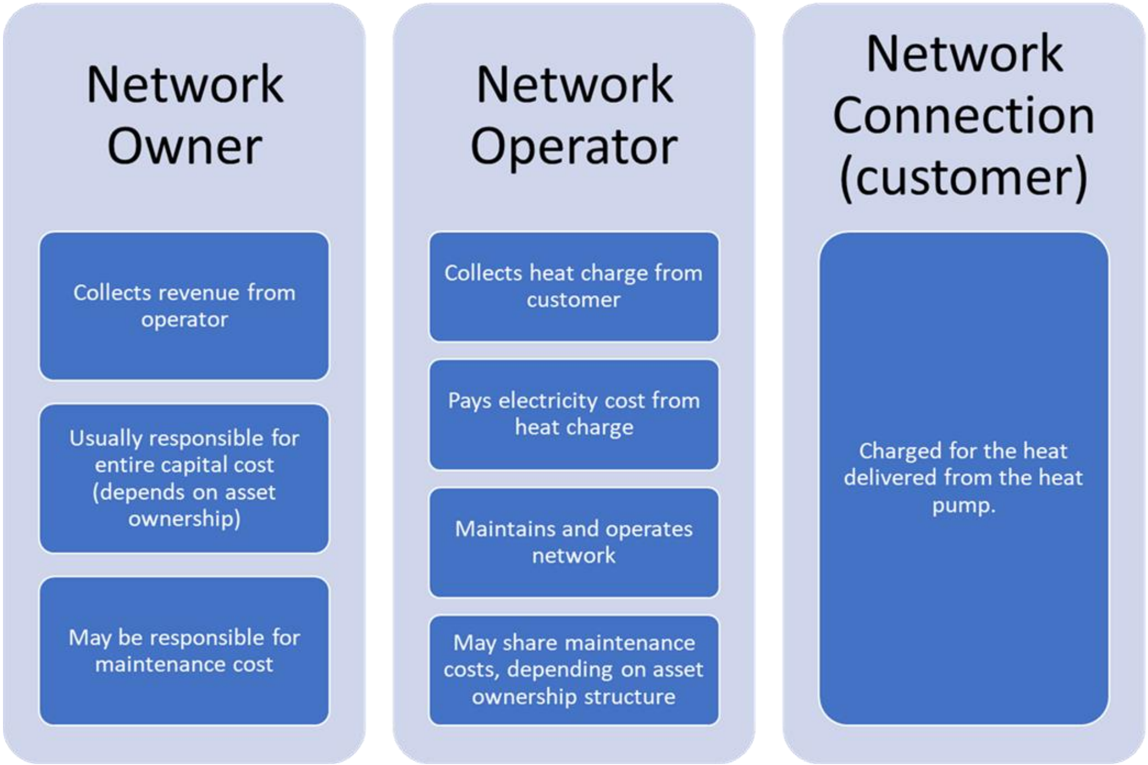


Figure 5-7 Bubble diagram of a potential 5G DHN asset ownership structure and responsibilities. This is only an example structure and should not be taken as a finite solution.

5.7.1. Technical Metrics: Installed Capacity

A summary of results is given in Table 6. This summarises key values for heat pump and TES sizing under energy sharing and non-energy sharing conditions. This is presented under fixed rate tariff, time of use tariff, fixed rate with carbon tax tariff, and time of use with carbon tax tariff.

For all tariff scenarios, the heat pump in heating mode had a lower installed capacity in the Fixed rate tariff than the equivalent time of use tariff (range=0.7MW, 10% diversity). For the heat pump in cooling mode, there is very little deviation in installed capacity for the energy sharing scenarios (range for energy sharing=0.2MW, 5% diversity) but the time of use tariff did have a slightly higher installed capacity. The installed cooling capacity is significantly higher in the absence of energy sharing (overall range=2.4MW, 70% diversity) and has a greater range within sub-scenarios (e.g. with/without energy sharing; range without energy sharing=1.7MW, 49% diversity). The time of use tariffs had a lower installed capacity of heat pump but higher installed thermal store. This implies a greater dependence on tariff structure in the absence of energy sharing.

There is only a small deviation in thermal storage across all scenarios in installed hot TES (range=5.4MWh). The range is greater for the cold TES (range=11.1MWh). This suggests an optimum TES capacity, which is not influenced significantly by the tariff structure for the hot TES. Tariff structure has much more significance for the cold side TES.

The installed capacity of heat pumps and storage was greater in the scenarios without energy sharing.

Table 5.6 Summary of Heat Pump and Thermal Storage optimisation results for installed capacity of hot side heat pump and thermal store, and cold side heat pump and thermal store under energy sharing and non-energy sharing tariff combinations.

	Tariff Structure							
	With Energy Sharing				Without Energy Sharing			
	Fixed Rate	Time of Use	Fixed Rate & Carbon Tax	Time of Use & Carbon Tax	Fixed Rate	Time of Use	Fixed Rate & Carbon Tax	Time of Use & Carbon Tax
Heat Pump Heating Max (MW)	2.0	2.7	2.1	2.7	2.3	2.7	2.3	2.7
Heat Pump Heating Diversity Factor (%)	28.0	37.0	29.0	37.0	32.0	38.0	32.0	38.0
Heat Pump Cooling Max (MW)	1.0	1.1	1.1	1.2	3.4	1.7	2.6	1.7
Heat Pump Cooling Diversity Factor (%)	30.0	34.0	32.0	35.0	100.0	51.0	77.0	51.0
Hot Thermal Store Capacity (MWh)	22.2	20.8	22.2	20.8	26.2	21.5	26.2	21.5
Cold Thermal Store Capacity (MWh)	10.0	11.1	8.0	11.1	0	12.6	3.0	12.7

The benefit of using 5G DHNs is to share energy between users. This is done by harnessing the offset (or rejected) heating or cooling from heat pumps. The shared energy should be considered carefully. If shared heat (provided by the cold-side heat pump) is utilised, this will reduce the demand on the hot-side heat pump. If shared coolth (provided by heat pump in heating mode) is utilised, the demand on the cold-side heat pump will be reduced. Therefore, there is a trade-off between utilising shared heat or shared coolth. Coolth for space conditioning is commonly provided by an electric air handling unit and heat pump. As electricity is more expensive than natural gas (for heating) it may be cheaper to provide the cooling from offset heat. However, if carbon savings is the objective then minimising natural gas usage should be the decision; therefore, it may be more beneficial to allow the cooling-led heat pump to operate and capture the offset heat.

In the case presented, shared cooling is used to offset the peak heating demand, which is shown by the lower heat pump heating diversity factor than heat pump cooling diversity factor in Table 6. However, the benefit is only significant with the fixed rate tariff. This would imply that the shared energy has minimal impact on the installed capacity. The tariff had a much greater impact on the installed capacity. This is likely because of the significant cost benefit the time of use tariff offered. At a low cost period, the heat/cooling in the scenario presented may cost as low as £0.004/kWh$_{th}$ (electricity cost £0.01227kWh$_{e}$ with COP of 3). If heat/cooling is generated at high cost periods, this could be as much as £0.0314/kWh$_{th}$. The time of use tariff offers a greater penalty for generating heat/coolth at high cost times than the betterment provided by the utilisation of shared energy. Therefore, there is a greater cost incentive to charge the thermal stores at low cost and discharge at high cost, than there is incentive to only utilise the energy sharing at peak times.

This scenario could change, if the demands on the network are significantly. However, in practice this would mean equal and opposite heating and cooling loads, which is unlikely to happen.

The carbon tax is a form of time of use tariff which uses a cost based penalty to encourage utilisation of low carbon electricity. These carbon tax scenarios offered almost no deviation from the non-carbon tax equivalent scenario. This is because the carbon tax penalty is too low to encourage a shift in response behaviour.

5.7.2. Tariff Structure and demand response

Figure 5.8 and Figure 5.9 show the optimised dispatch response for a peak heating and cooling 48 hour period. The first column graphs show the dispatch response with energy sharing; the second column graphs show the dispatch response with no energy sharing. The red line shows the heat pump response.

In the fixed rate scenarios, the heat pump operates below the demand (green line) for the majority of the period. For the equivalent time of use tariff, the heat pump operates an almost inverse of the cost (black line, second axis). The instantaneous demand is met almost entirely from direct production and energy from the thermal store (ie there is little energy sharing utilised at peak periods).

The heat pump operates slightly higher in the scenarios with no energy sharing when compared to the scenarios with energy sharing. This deviation is very marginal.

The scenarios with a carbon tax were almost identical to the equivalent scenario without the carbon tax.

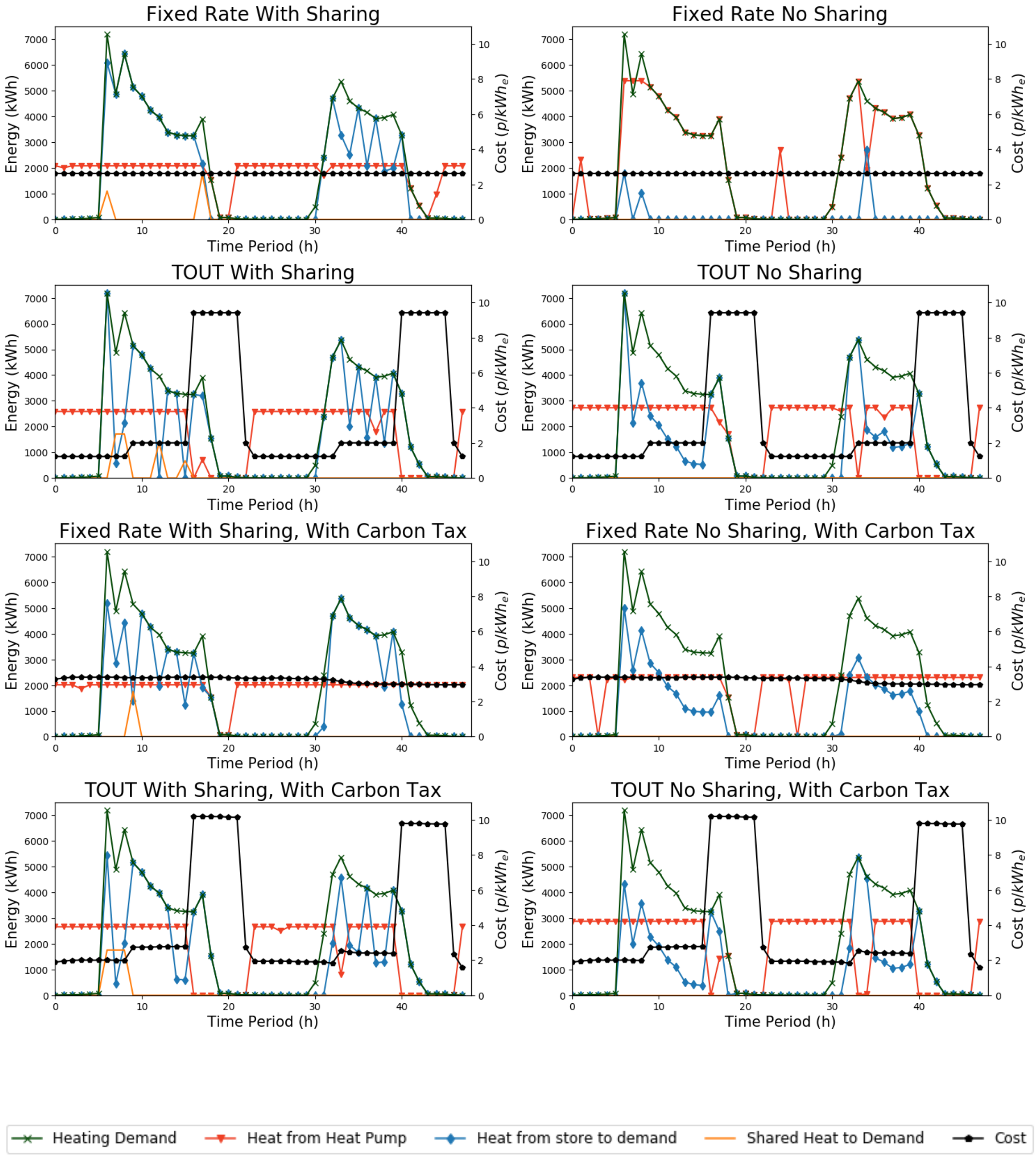


Figure 5-8 Hot-side dispatch profiles for tariff structures (TOUT, Fixed rate, and Carbon Tax). Scenarios with energy sharing are shown in the left hand column, while non-energy sharing is shown in the right hand column.

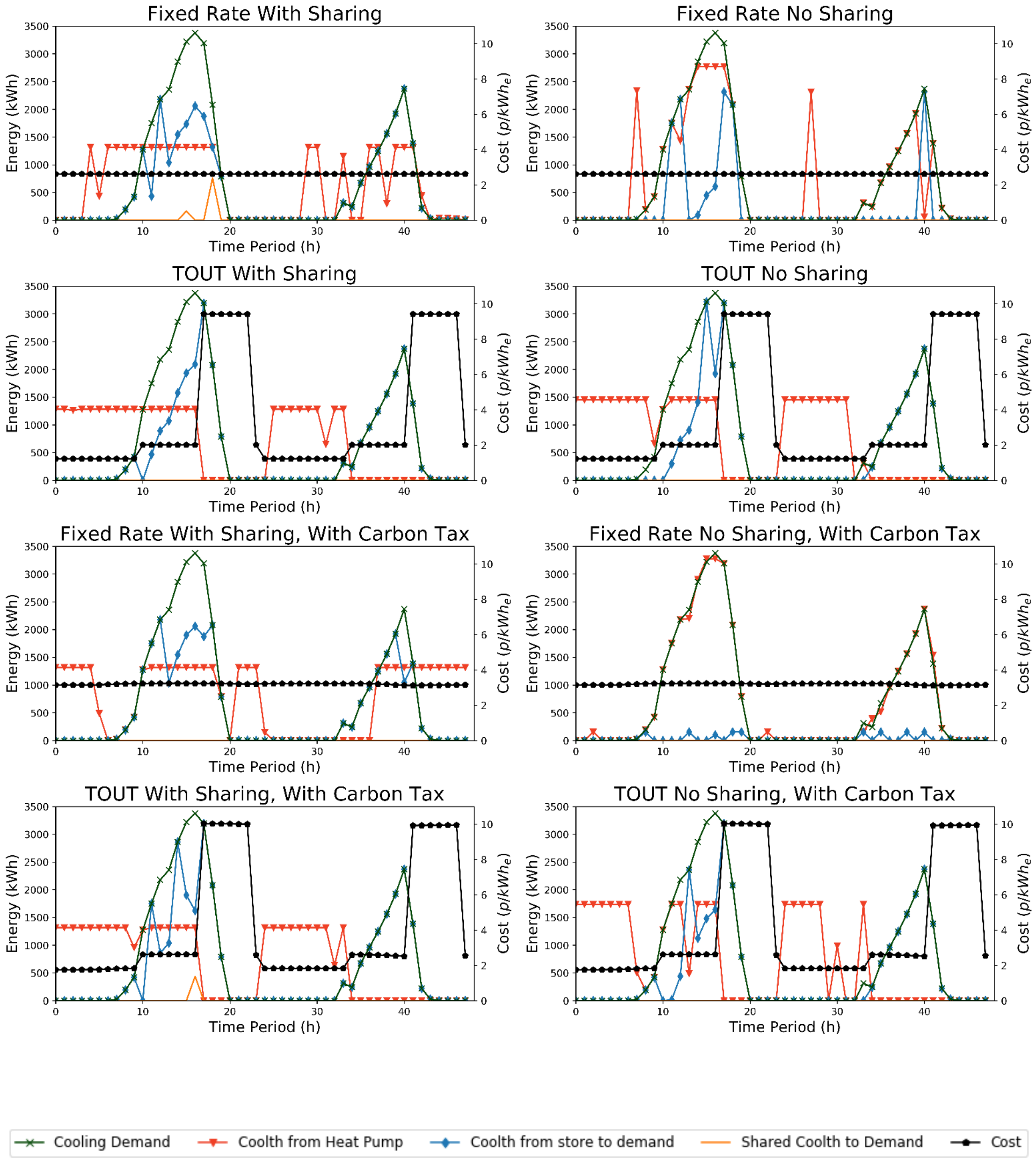


Figure 5-9 Cold-side dispatch profiles for each tariff structure (TOUT, Fixed rate, and Carbon Tax). Scenarios with energy sharing are shown in the left hand column, while non-energy sharing is shown in the right hand column

From Table 5.6, the fixed rate tariff had a lower diversity factor for installed hot side heat pump capacity compared with the time of use tariff for all scenarios. These differences can be further understood by considering Figure 5.8 and Figure 5.9. These figures show the heat pump operating profiles for peak heating and cooling days. For the time of use tariff, the heat produced by the heat pump (red line) follows a recurring pattern, where the heat pump operates above the demand (green line) to charge the thermal store at lower cost periods and switches off during high cost periods, in a peak shifting strategy [43].When the higher cost period occurs, the heat pump switches off and the heat from the store (yellow line) follows the demand. However, at certain high cost periods the heat pump capacity is too small to follow the demand. Instead, the heat pump operates at full capacity while supplementing from the thermal store, moving from peak shifting to peak shaving [43, 44]. This is the optimised trade-off between the heat pump capacity and the TES capacity, accounting for the tariff structure. Saffari, De Gracia [45] reports a linear increase in cost saving with increasing TES capacity when a TOUT is utilised; this is supported by our findings but is not the full picture. The overall financial benefit (i.e. NPV) is sensitive to the cost of storage and the range of high/low cost periods. The optimisation is performed over the range of values and is therefore aware of the predicted peak load and has not accounted for loss from the tank, which may diminish the benefit of this type of demand side management in practice. However clear benefit is shown in reducing the impact electrification of heat may have on the national electricity grid [46, 47].

In the fixed rate scenario and when there is no sharing, there is no financial benefit to charge the thermal store and so the heat pump follows the demand. However, when the demand peaks, it is better financially to minimise the peak load of the heat pump, and so prior to the demand increase the heat pump operates above the demand to charge the store. This discharges during peak period, reducing peak electrical demand in a peak-shaving operation. The financial benefit is found by minimising the necessary capital investment, rather than operational benefit.

The carbon-taxed tariff introduces in incentive to move away from energy production at high carbon intensity periods; these are essentially a variation of TOUTs. However, the carbon-taxed dispatch profiles in Figure 5.8 and Figure 5.9 do not show significant deviation from the non-carbon-taxed dispatch profiles. In this case, the carbon tax is too small to drive a change in operation. The greatest influence on reducing carbon emissions was found to come from utilising energy sharing, shown in Table 6, followed closely by the presence of TES and the carbon tax. The hourly grid carbon intensity is anticipated to decrease significantly across the 25 year modelled lifecycle. This means the impact of a carbon tariff is expected to diminish as the grid de-carbonises. However, this study does not present a full lifecycle carbon assessment to account for the embodied carbon of equipment. If the embodied carbon of the installed equipment is included, this may encourage greater diversity, but further investigation is needed to confirm.

Energy sharing may reduce the installed capacity, but only when there is financial benefit, or there is a significant coincident heating and cooling load at peak periods. The peak heating demand is in December and the peak cooling demand is in July. Figure 5.6 shows very little cooling demand in the winter and very little heating demand in the summer. This can explain why the diversity of installed heating plant equipment is not significantly affected by the ability to exchange heat or coolth, shown in Table 6. However, the diversity of the cold side equipment varies much more significantly. This is because there is much more shared cooling than there is shared heating, and the cooling demand is much smaller than the heating demand. This means the shared energy will have a greater impact on cooling diversity.

When energy sharing is allowed, across all three scenarios, the amount of energy being shared does not deviate significantly. The cooling demand is met by 5% shared cooling, while the heating demand is met by around 20% shared heating. The smaller share of shared cooling utilisation is to be expected due to the lack of simultaneity, discussed above. The useful shared heating utilisation (shared heat to demand and store) is almost identical in all cases. This suggests there is a point of maximum shared benefit which is independent of the tariff. This supports the idea that it may not be financially beneficial to utilise all shared energy potential. Further study is needed to explore this concept.

5.7.3. Design Metrics for Energy Sharing

Figure 5.10 shows how the demand was met for the different tariff structures. The cold side is almost exclusively met directly from the cold side heat pump, but the hot side utilises much more offset energy. The total utilised shared energy is almost the same for all tariff structures (approx. 80% of total energy supply) but the ratio of shared energy used directly to meet demand compared with the energy sent to store varies. The scenarios with carbon tax stored more energy than the scenarios without a carbon tax.

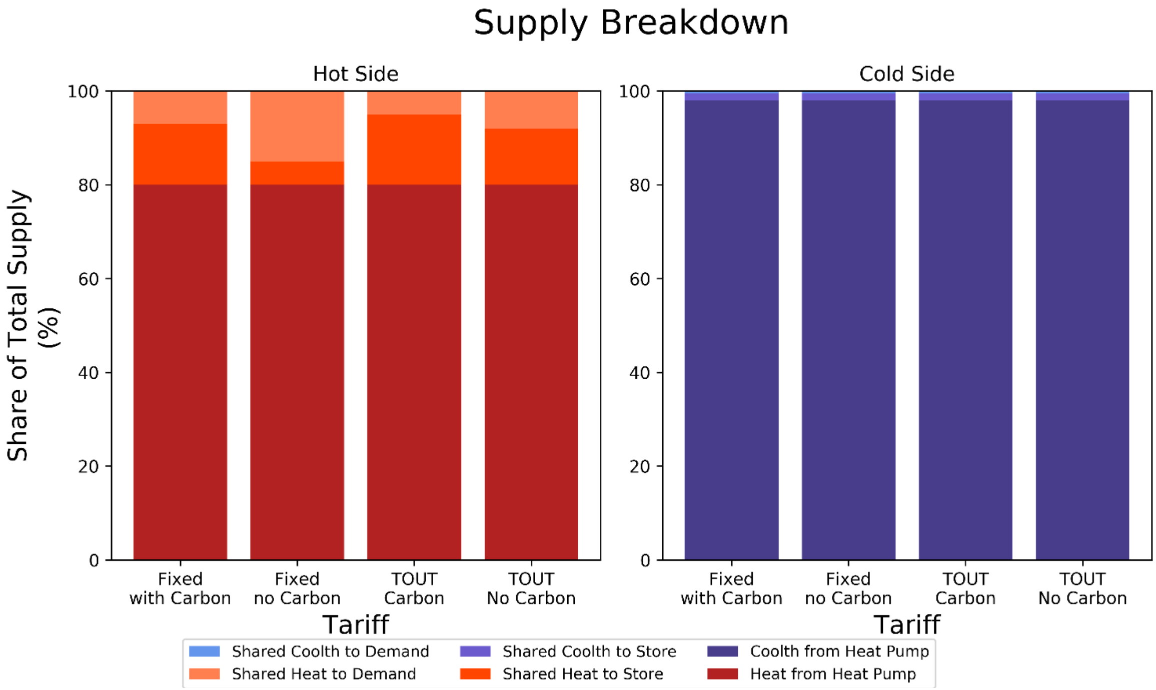


Figure 5-10 Bar graphs showing how the shared energy of each scenario is used as a percentage of total demand. The hot side break down is shown on the left, while the cold side break down is shown on the right.

Figure 5.11shows how the shared energy is utilised with and without thermal storage. As Figure 5.10 showed, almost none of the offset cooling is utilised in any scenario.

When thermal storage is used with fixed rate tariff, there is the same overall offset energy usage as in the fixed rate tariff with no thermal storage. The time of use tariff benefits more from thermal storage and therefore utilises more shared energy when there is thermal storage. The carbon tax scenarios follow similar trends but the time of use tariff does not utilise as much offset energy as the time of use scenario without the carbon tax.

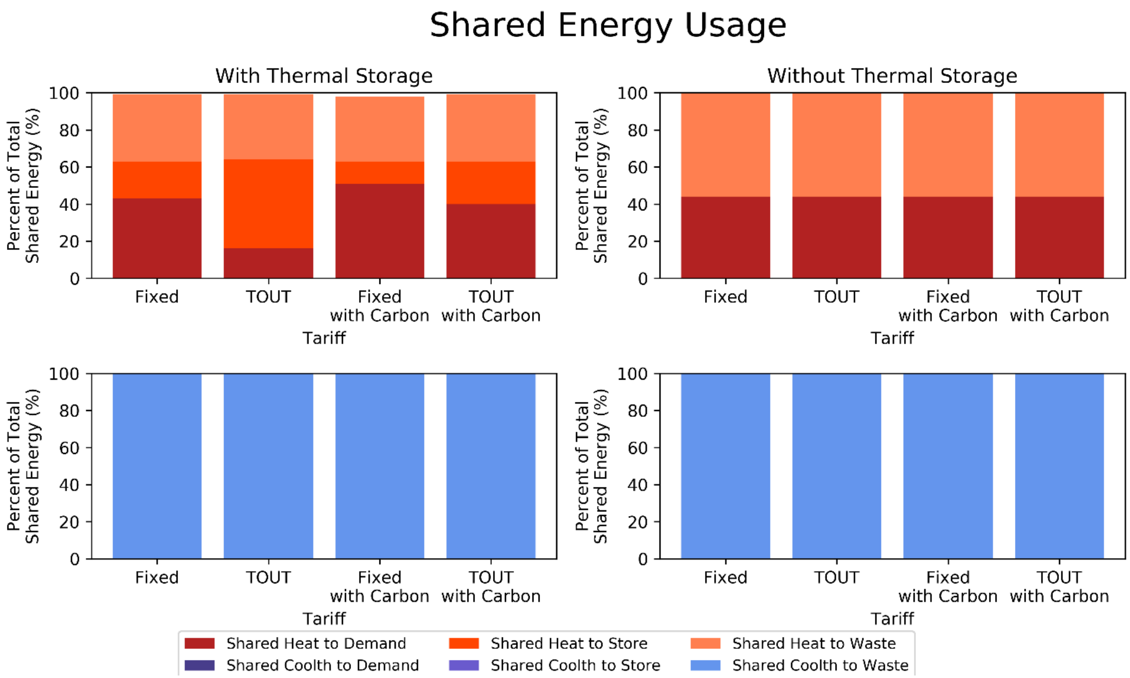


Figure 5-11 Bar graphs showing how the shared energy is used as a percentage of the total shared potential. Hot side data is presented in the upper two plots, while cold side data is presented in the lower two plots. The left two plots show scenarios utilising thermal storage, while the right two graphs show scenarios which are not utilising thermal storage.

Figure 5.12 shows the levelized cost impact of energy sharing and thermal storage on the cost per kWh of energy supplied (i.e. the levelized cost of energy). The time of use tariff had a lower LCOE than the fixed rate tariff when thermal storage was used, but higher when only energy sharing was used with no thermal storage. The thermal storage had the largest impact on the levelized cost. Adding storage without sharing reduced the time of use tariff LCOE by approximately 50% and the fixed rate by 14%. Adding sharing and no storage reduced the time of use tariff LCOE by 12.5% and the fixed rate by 7%. This implies that, even under a fixed rate tariff with no time based usage penalty, thermal storage made the biggest improvement on LCOE and energy sharing offered little financial benefit.

As expected, the LCOE is highest when there is no sharing/storage, and lowest when there is sharing and storage. This supports the previous conclusions; thermal storage is necessary to achieve the lowest costs, with energy sharing being of greatest benefit when used in conjunction with a time of use tariff and thermal storage. There is a 69% reduction in levelized cost between the highest cost scenario (time of use tariff, no sharing, no storage, with carbon tax) and the lowest cost scenario (time of use tariff, with sharing and storage), but only a 63% reduction between the highest cost and second lowest cost (time of use tariff, no sharing, with storage). This cost analysis was simplified and therefore omitted many additional costs; the financial benefit would be even lower if they had been included. Therefore, it is unlikely there would be a significant financial value in energy sharing under the conditions of this study. However, it is difficult to attribute the long term financial cost of global warming. Climate benefits must also be considered when assessing viability.

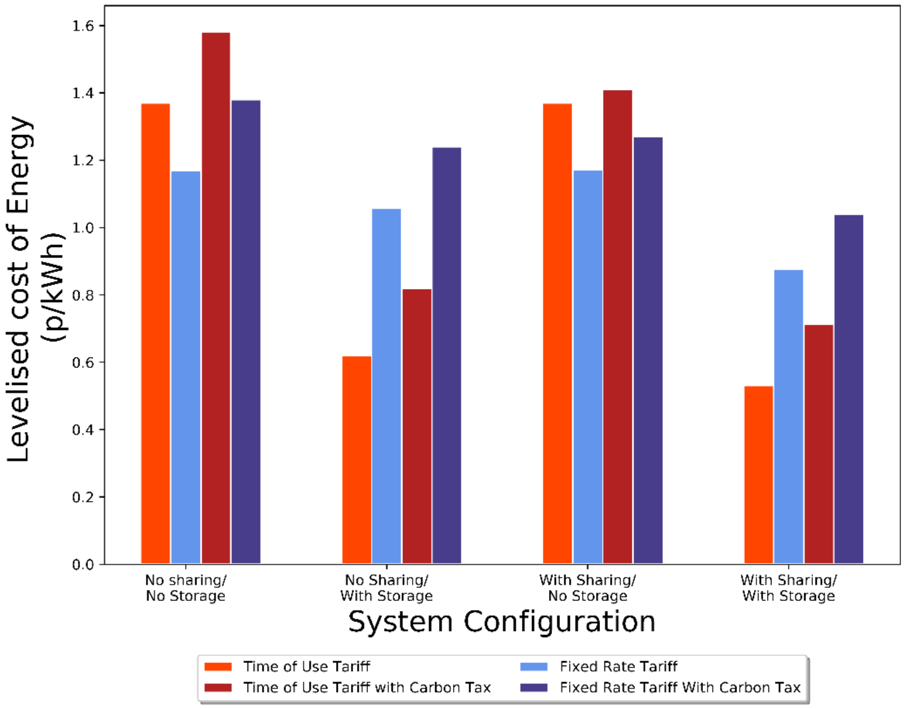


Figure 5-12 Levelised cost of energy comparison for Time of use Tariff and Fixed rate tariff, both with and without carbon taxation. Data presented is for four different system configurations. Time of use tariff data is shown in orange tones, while fixed rate tariff data is shown in blue tones.

5.7.4. Overall Design Metric Importance

Figure 5.13 provides a summary of metrics used for each variable. Each column is the average of all 16 scenarios.

The largest impact on performance was the availability of thermal storage. The NPV with thermal storage was 20% higher than without. Energy sharing had a much smaller impact on NPV (7.7% higher with sharing than without). The LCOE was 50% higher without thermal storage, but only 22% higher without energy sharing.

On average, the tariff had no impact on the shared energy usage but had an impact on NPV and LCOE. The carbon emissions were reduced by using storage and energy sharing, but the largest benefit was from energy sharing (12.5% reduction when energy sharing is used, 6% reduction when energy storage is used).

This study investigated 16 distinct scenarios to assess the merits of an energy sharing network. Some of the key variables from the study were averaged across all scenarios and summarised in Figure 5.13 to easily identify the variables with largest impact on the sharing network. Across all scenarios and variables, thermal storage had the greatest impact. The scenarios show that thermal storage is the key variable when it comes to sharing energy. The tariff structure had almost no effect on the total quantity of energy shared. This is supported by Figure 5.11, which shows a critical point of energy sharing. This suggests a point above which energy sharing is no longer financially beneficial. For this study, around 60% of shared potential was utilised across all scenarios with storage, while 40% was utilised across all scenarios without storage.

The tariff (either time of use or fixed rate) granted benefit in some places. Using a TOUT, on average, showed benefit for the cold side heat pump diversity, but not for the hot side heat pump. In this scenario, it is because the hot side heat pump must operate at higher capacity during the low cost periods, without having the benefit of relying on the shared heating to reduce the peak. This is contrary to the cold side, which can be supplemented by the shared cooling all year round as there are few times when the heating demand drops to zero.

The carbon tariff offers almost negligible carbon savings across all scenarios. This is because the carbon tax is too low and can therefore be mitigated through marginally higher thermal store. This has been identified as an issue globally and is an ineffective method of reducing carbon emissions [48].

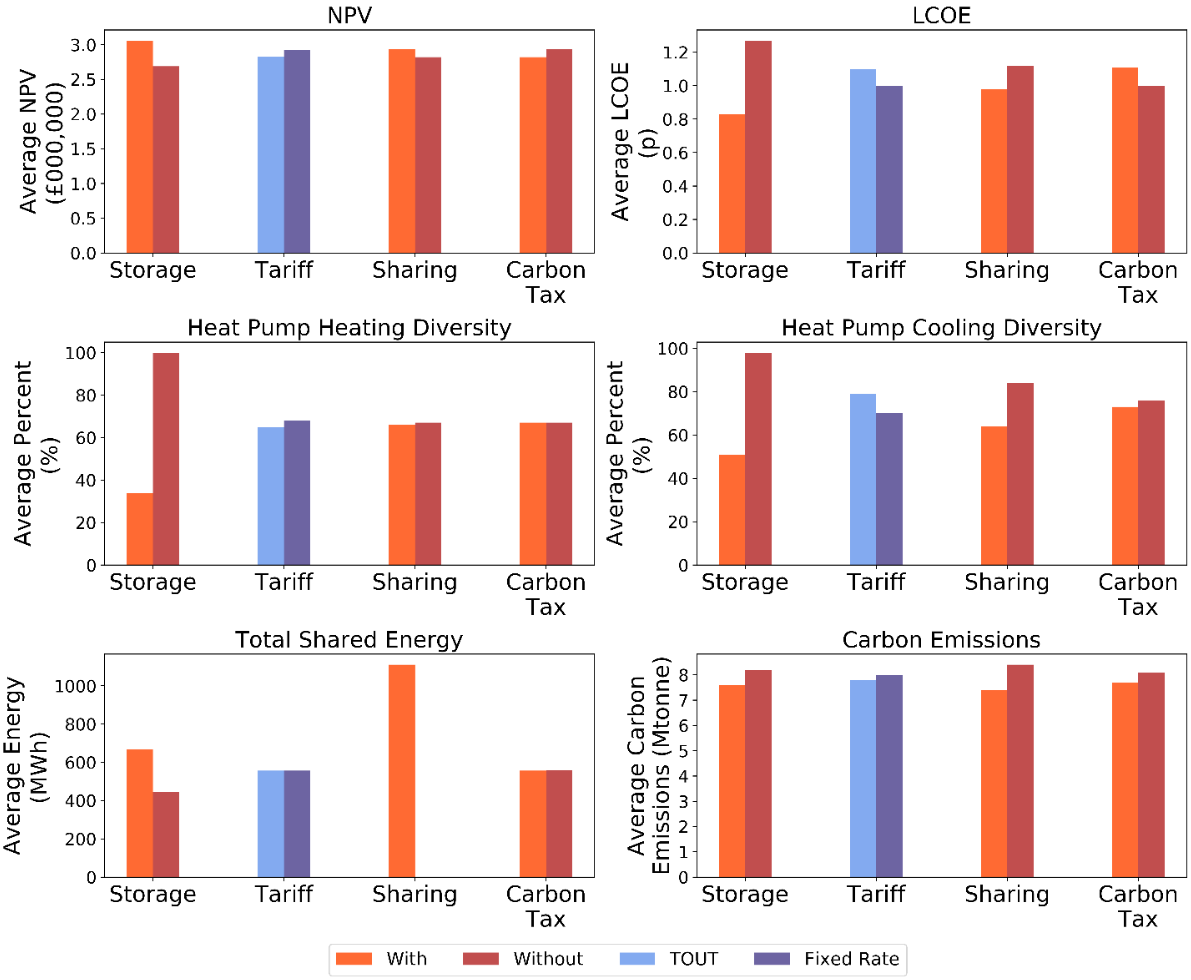


Figure 5-13 Aggregate Averages of key variables. The orange bars show the average of scenarios with the variable, the red bars show the average without the variable. Light blue bars are the average of TOUT, while dark blue is the average of the fixed rate tariffs.

5.7.5. Complimentary Heating and Cooling Loads

To fully appreciate the energy dynamics of an energy sharing system requires in depth, detailed analysis. This can be both time and financially expensive. It is therefore important to be able to draw generalisations from available data that can be used as a high-level tool to inform early stage design discussions, which is the intention of Figure 5.14.

Figure 5.14 shows the percentage of shared energy which is not economically viable to utilise. The best case scenarios are calculated via the method shown in 2.1 above and the total wasted shared heat ($Q_{offset,H,k}$+ $Q_{offset,C,k}$) is calculated from these results. This is shown for 1156 different combinations of heating and cooling loads on a per m^2 basis. Where two of the same type are shown, this indicates a greater share of that type. For example, “Office, Office” would be twice as much office space. For example, the upper left corner is “Office heating and office cooling”. This shows that 92% of the potential shared energy is wasted when an office utilises the offset energy produced from heat pumps. The scenario below, “office heating and retail cooling” only wastes 86% of the energy, and is therefore a better choice.

Looking vertically, it is difficult to see any trends in shared heat usage, however there are clear trends horizontally with the chosen cooling loads. From the data, it would appear that there is little to no benefit to using residential or hotel cooling loads in an energy sharing network as the wasted shared energy is always close to 100%. This is expected as residential space in the UK does not have the facility for space cooling and the hotel cooling demand is negligible. As there is no sizable cooling load, there is no benefit of energy sharing. However, the heating loads could still be used and paired with a promising cooling load.

The best choice of heating load is office space. On average, this has the lowest wasted energy. The retail space was found to be the best option for a baseload cooling demand. These options can be understood by considering Table 3. The office and retail space both have a reasonable heating and cooling demand, while the other building types do not. This creates the potential for shared energy to be stored for later use in the building. If one building produces heat, the offset coolth that is produced can be stored for use in the same building at a later time because there is the demand. This suggests that there is benefit of using the offset energy in the one building, either between different space conditioned zones via smart management or potentially through energy storage. However, it is unclear if there is greater benefit from sharing energy between buildings or simply smarter internal usage. This approach may work for building types with mixed energy demands (e.g. retail/office) but will not offer benefit to those with a single large demand (e.g. residential/hotel).

On considering how wide to make connections to a network, there is a compromise on how many buildings to connect to the thermal demand density. As more buildings connect, the demand density has the potential to diminish leading to higher distribution losses. From Figure 5.14, the configuration with three building types had the lowest wasted energy. The largest cause of wasted energy comes from the shared coolth. The shared energy can be utilised because there is a significant amount of shared heat used immediately but also because there is always a heat demand across small time horizons; this is either from space heating or the year-round domestic hot water demand.

The analysis offers a first-pass guide intended for early stage design, not to replace detailed design and analysis. The limitations of the analysis must be acknowledged when considering the data in Figure 5.14.

The energy loads are for a very specific combination of building types. While this can be indicative of a typical urban street, variations may still occur which will vary largely depending on factors such as occupancy profile, location, building age/thermal performance and orientation.

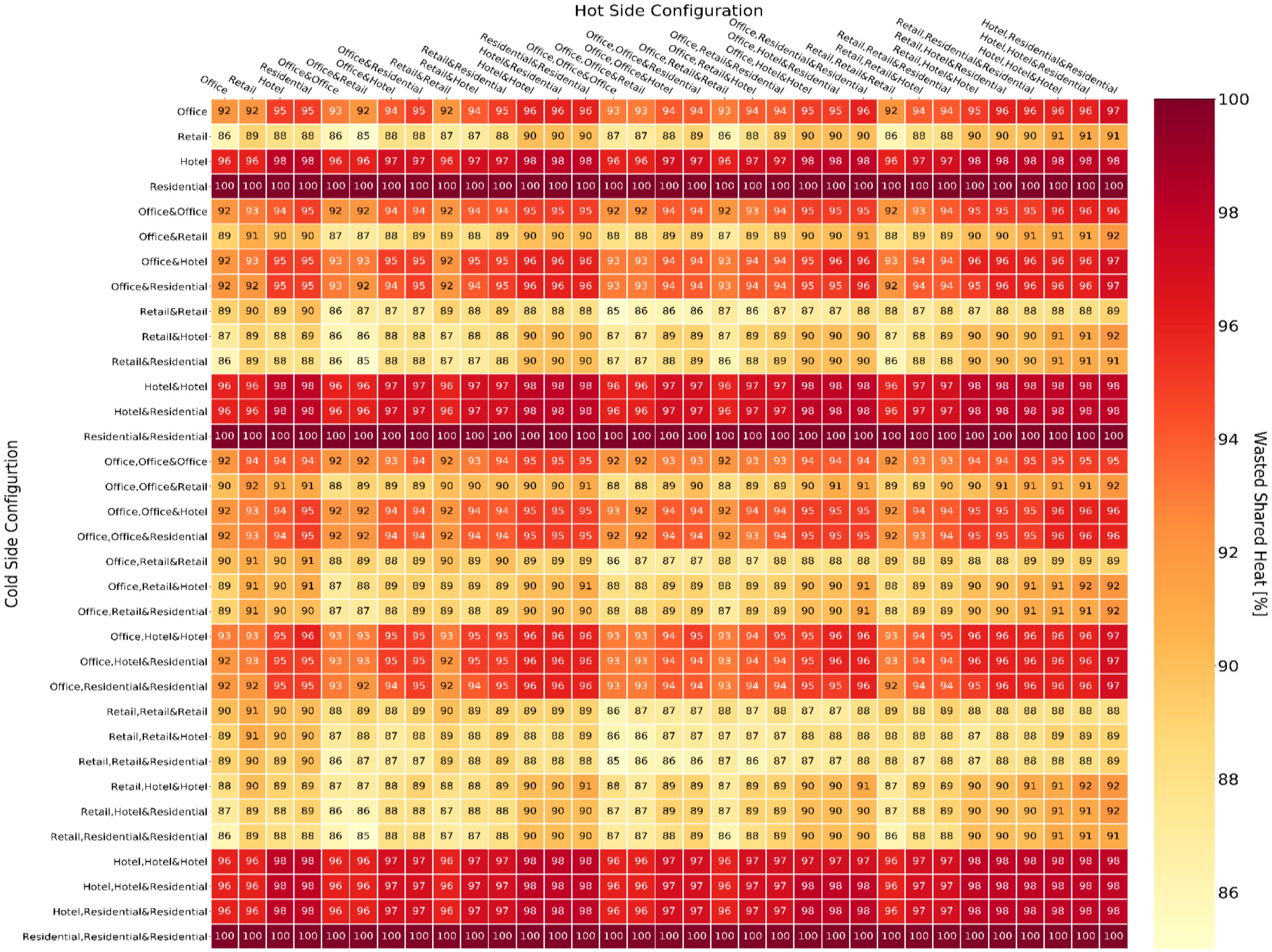


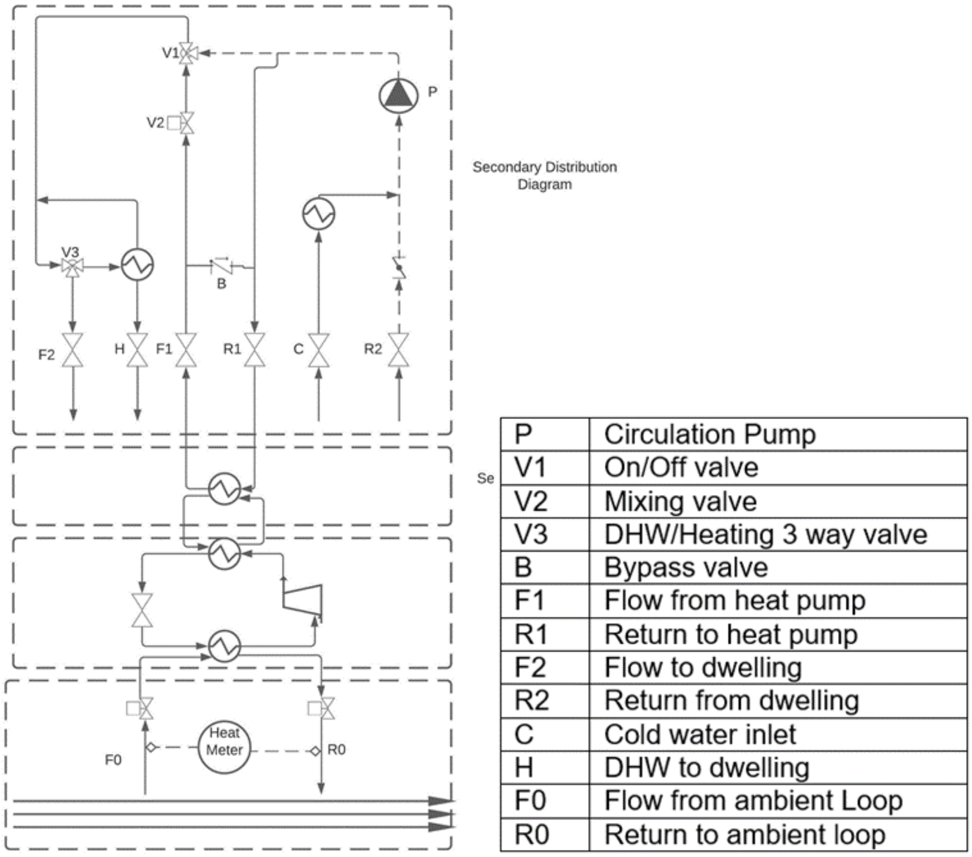
Figure 5-14 Heat Map of Wasted Shared Energy. Lighter colours show better scenarios (less wasted shared energy). Connected hot side demands are shown in the X-axis, while cold side demands are shown in the Y-axis.

5.8. Study Limitations

As with all computational projects, a number of assumptions have been used throughout the study which will introduce a degree of error.

The most significant error we can see is in reducing the model to a static input, rather than a full dynamic model of the distribution network. By taking a static model, we remove the need to consider system level dynamics (e.g. heat exchanger pinch points, internal thermal mass and inertia, secondary distribution) and therefore present a less detailed but cleaner comparison of the complimentary loads on the network. We believe this is suitable for a network level consideration (i.e. the point of network operator) as in practice, the network operator is only interested in meeting the demand. In a traditional heat network, the operator must maintain a minimum flow rate and temperature, but in a 5th generation network the deviation in grade of heat being supplied by the network is inconsequential as the secondary circuit is designed for low grade heat. Therefore, the operator is only concerned with the energy being absorbed/rejected from/to the network to remain within a much broader operating dead band.

However, from the perspective of the secondary distribution (i.e. from the heat pump) the difference between ambient loop temperature and heat emitter supply temperature is of greater importance. This can only be considered in detail with a dynamic simulation accounting for all loads and control response on the distribution network, therefore not considered here. As building fabric improves, it is likely the need for high temperature secondary loops will reduce, therefore minimising the errors of this assumption.



P	Circulation Pump
V1	On/Off valve
V2	Mixing valve
V3	DHW/Heating 3 way valve
B	Bypass valve
F1	Flow from heat pump
R1	Return to heat pump
F2	Flow to dwelling
R2	Return from dwelling
C	Cold water inlet
H	DHW to dwelling
F0	Flow from ambient Loop
R0	Return to ambient loop

Figure 5-15 Suggested hydraulic circuit diagram of heat meter location and measurement points, showing heat metering taking place at the property boundary and interface between the ambient loop and end user.

5.9. Conclusions

This paper assesses the key performance indicators and metrics around 5th generation district energy sharing networks. A number of financial and technical metrics which are commonly used throughout design have been assessed for a European case study using dynamic building energy modelling, combined with linear programming. The network is assessed from the network operator perspective with the intention of providing novel research to support early stage design, and operation strategy. The optimisation algorithm is designed to select the most cost effective sizing of equipment (hot and cold side heat pump and thermal storage), and demand response approach. The demand response approach includes an optimal use of storage and capacity to maximise the Net Profit Value. In total, sixteen scenarios are tested and analysed in detail. These include scenarios using a fixed rate or time of use tariff, using thermal storage or no thermal storage, using energy sharing or no energy sharing, and using a carbon levy or no carbon levy.

We can conclude that:

- The largest promoter of energy sharing is the utilisation of thermal storage. Heating and cooling demands are rarely simultaneous and so it is necessary to store the shared potential for later usage. Some scenarios tested showed 82% shared energy utilisation with energy storage, compared with only 40% shared energy utilisation without. The Levelised Cost of Energy was 50% higher without thermal storage.

- Energy sharing did not have a significant impact on any of the metrics assessed. While energy sharing did offer improvements, these improvements were dwarfed by the benefit provided by utilising a time of use tariff or a thermal store. Energy sharing was able to show a 12.5% reduction in the Levelised Cost of Energy.

- Some building types are inherently better suited to sharing energy between users. The more users are connected to the network, the more likely shared energy is able to be utilised. From the energy demands assessed, a 14% increase in utilised shared energy can be achieved from connecting complimentary loads. Some demands are inherently poor matches for sharing (e.g. hotels and residential) where the energy demand is particularly heavy in one side. In this case, the heating demand was much greater than the cooling demand. Others are inherently much better, such as office space, where there is a year round mix of heating and cooling demands

- Tariff structures have a significant impact on operating strategy, operating cost, and therefore profitability. In some tested scenarios, the levelized cost was more than 33% less when using a time of use tariff, compared to the equivalent scenario with the fixed rate tariff. However, if there is no means of demand side management, the time of use tariff can be 69% more expensive than the equivalent scenario with demand side management.

- The rate of carbon levy is significantly too low to have any significant impact on either the operating strategy or the equipment sizing and selection. Energy sharing showed a 13% improvement on carbon emissions when compared with an equivalent non-sharing network, but this is un-related to the carbon levy. The cost per tonne of carbon dioxide would need to be significantly higher to force change in operation, and therefore further reduce carbon emissions.

This study utilised a number of assumptions, primarily around the performance of the heat pumps and the operating temperatures of the ambient loop. Further research is needed to better understand the dynamic interaction of energy demands on the sharing network, the selection of ambient loop temperature, and the demand response needed for a well performing energy sharing network.

5.10. Future Work

It is acknowledged that this study has used a number of simplifications which can be improved upon in future work to improve the representation of physical characteristics. Most notably, the study assumes a static coefficient of performance for the heat pumps. This is only likely to be a close approximation for high performance buildings, with low temperature heat emitters and Legionella prevention which is not temperature dependent (e.g. chlorine dosing, UV treatment). For retrofit applications, the efficiency will vary across the year depending on set point temperatures.

The dynamics of the ambient loop have not been considered in detail here. We have assumed that any energy rejected into the loop can instantaneously be used anywhere else on the loop, which may not be true in practice due to hydraulic lag. It is expected that the energy rejected from a single user will not be significant enough to make drastic change to the loop temperature, but is yet to be shown in literature.

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6. Operational optimization of 5th generation district energy network

6.1. Introduction

Decentralized energy systems have an important role to play in achieving Net Zero carbon emissions. Producing and utilizing energy locally can, under certain circumstances, provide flexibility [1], stability [2], and improved energy security to the wider power infrastructure [3]. In the past, District Heating Networks (DHNs) have often suffered from high thermal losses [4], poor integration of waste resources due to high operating temperatures [5], and limited flexibility in operation (e.g. reducing supply temperature/flow variation) [6]; this has created challenges in decarbonizing heat networks [7]. It has been suggested that 5th Generation District Heating Networks (5GDHNs) may be able to address some of these challenges.

5GDHNs are district energy networks which allow thermal energy sharing between users connected to the network. They have also been termed as "Cold District Heating Networks" [8], "Bidirectional low temperature networks" [9], and "Close to ground" or "ambient" temperature networks [10] . Traditional heat networks have several limitations which may be addressed by 5GDHNs; high distribution temperature [11], oversized distribution pipework [12], seasonal variations in demand [13], and preventing monopoly markets [13]. A principle feature of 5GDHNs is the ability to provide simultaneous heating and cooling [14]. This can be achieved through decentralized, reversible heat pumps. This allows users connected to the network to move away from the traditional model of "single direction" consumers and move towards "bidirectional" prosumers, where the user is able to absorb heat (and therefore reject coolth) or absorb coolth (and reject heat) from/to the ambient temperature network. There have been many studies which present waste energy sharing (often data centers), however these have very often only been between two users, such as the studies presented by Khosravi, Laukkanen [15] and Luo, Andresen [16]. These studies have a lot of value in developing the principles of 5GDHNs, but for the purpose of this study are considered too small to fall into this definition and we would categorize as "waste heat recovery" rather than "district heating".

The selection of operating temperatures within district heating has been discussed in many previous studies. Volkova, Krupenski [17] discuss the possibility of providing low temperature district heating (40-50°C) from the return line of a high temperature network. Liu, Zhou [18] present a temperature-variable control strategy for space heating provided by district heating. Meesenburg, Ommen [19] compare the economic feasibility of “ultra-low temperature district heating” (circa. 40°C supply) with low temperature district heating. Gustafsson, Delsing [20] examine the relationship between primary supply temperature in district heating with the secondary network control strategy and heat emitter calibration. None of the studies currently presented in literature give significant focus to the supply temperature for 5GDHNs. If heat pumps are adopted in 5GDHNs, the supply temperature in the network will have a significant impact on the Coefficient of Performance (COP) of the network. This is complicated by the opposing goals; increasing the supply temperature may benefit the efficiency of heat supply but will reduce efficiency of coolth supply. Similarly, reducing the supply temperature will benefit the efficiency of coolth supply, but reduce efficiency of heat supply.

Heat networks operate best when the length of distribution is minimized to keep the demand density as high as possible and are therefore most often deployed in urban areas [19]. There are often restrictions on the routes which can be used to lay heat network pipes, and it is rare to have every available customer on a network route connected to the network. This creates the issue of route selection, or “topology optimization”. A significant issue in topology optimization is the computational limits the flow, heat transfer, and equipment selection can bring. Blommaert, Wack [21] present an impressive solution to this by proposing a numerical continuation strategy. Equipment selection can be described as a “discrete” problem; there is a limited number of options to choose from. Söderman [22] uses a discrete Mixed Integer Linear Programming model to solve the topology problem for a district cooling network. This approach has a lot of merit in reducing the computational cost but does not fully capture the non-linear costs of fluid distribution. Bordin, Gordini [23] use optimization techniques to assess the cost benefit of extending an existing heat network. This approach uses a piecewise linear approximation of the non-linear pressure drop curve. This method ultimately reduces the non-linear constraints to a linear integer problem, with good approximation within each respective discrete flow region. Similar topology studies have also been presented by Haikarainen, Pettersson [24], Omu, Choudhary [25], and Vesterlund, Toffolo [26]. All of the studies presented focus entirely on traditional single directional heat networks. To the best of our knowledge, there are currently no studies which discuss the topology optimization of 5GDHNs.

In the optimization of heat networks presented in literature, the goal (or objective function) is most commonly a form of cost function; as such, there are many techno-economic studies in literature. Koch, Höfner [27] compare a biomass fired CHP heat network with natural gas fired CHP. The study gives a detailed technical comparison, but only limited focus on long term economic metrics. Kim, Kim [28] appraise a hybrid solar thermal and heat pump system district heating network. Levelized Cost of Heat (LCOH) and Net Profit Value (NPV) are used as financial indicators of viability. Arnaudo, Dalgren [29] discuss the viability of waste heat recovery integrated heat network compared with individual domestic heat pump solution (i.e. each customer has their own heat pump). Again, this study uses NPV and LCOH as indicators. The study concludes that localized domestic heat pumps cannot meet the entire user demand; this is primarily due to limitations in the current electrical distribution grid. Arguably, this problem will be addressed as many nations intend to significantly increase electrical transmission capacity to support the electrification of heat. A similar techno-economic appraisal is given by the same research group, Arnaudo, Topel [30], with the intention of promoting electrical demand peak reduction via demand side management.

6.1.1. Contributions

The literature review presented above has identified a number of gaps within the current literature. This paper addresses these gaps; we present a dynamic model of a 5th generation district heating and cooling network. The methodology is applied to a selection of case study demand profiles to identify optimal load placement. A detailed analysis of the ambient loop dynamics is presented. This is intended to support early masterplan design.

The key contributions are:

- To identify the impact of load topology on the overall system efficiency (i.e., where should demands be placed to optimize the wider network)

- Optimize the design temperature of the ambient loop based on shifting energy demands

- Identify the significance of linear demand density of the overall technical performance of the network.

6.2. Theory

This section describes the fundamental theory and assumptions used throughout the study.

6.2.1. Business Model

The assumed business model must be defined to allocate cost, carbon, and energetic benefit to stakeholders on the network. For this study, it is assumed that the network operator owns all assets relating to primary energy center, primary distribution, and secondary energy center. The operator is responsible for initial financing, ongoing maintenance, and operation of these sections. The operator will recoup these costs from energy sales to the customer. The chargeable energy is the energy delivered to the secondary distribution. The secondary distribution is the responsibility of the network customers and is not considered in detail here. This is summarized in Figure 6.1.

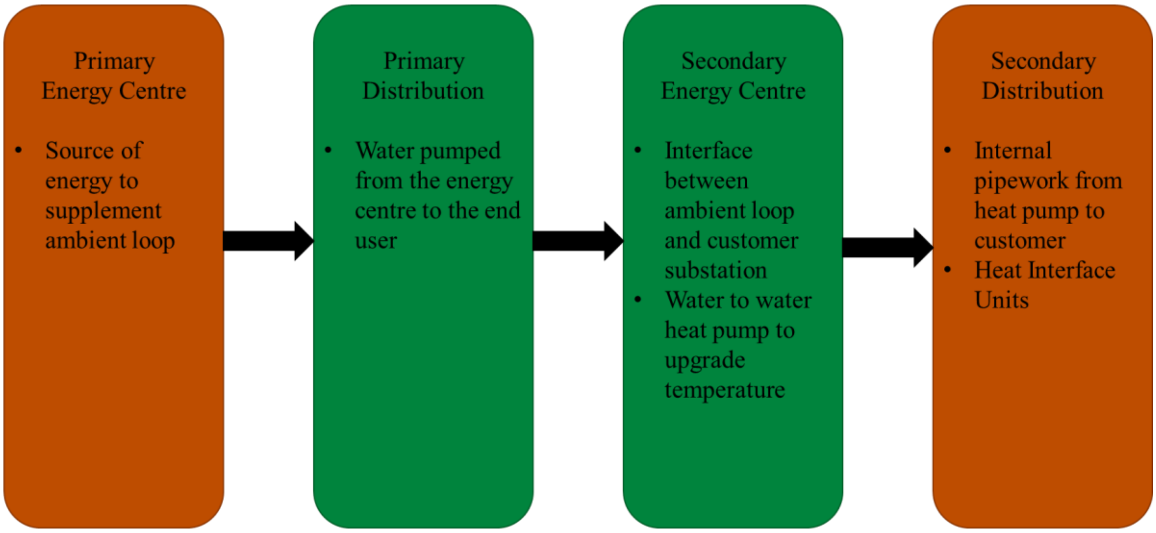

Figure 6-1 Diagram of ambient loop network section divisions showing the key roles of each section. The sections in green are the key focus of the study. Sections in orange are considered but not analyzed in detail.

6.2.2. Economic Modelling

The objective is to identify the financial and energetic benefit of utilizing energy sharing in an ambient loop network. For the network to be adopted in practice, it must show a financial benefit. For this reason, the objective function is formulated to minimize the annual cost of the network. This is shown in Equation 26 and 27. C_T is the total cost, C_C is the capital cost, and C_O is the hourly operating cost, all in GBP.

$$Total\ \ Cost = Capital\ \ Cost + Operating\ \ Cost \tag{26}$$

$$C^T = C^C + \sum C^O \tag{27}$$

The capital cost is the total investment cost, shown in 28 and 29.

$$Capital\ Cost{=}Primary\ Heat\ Pump\ Cost{+}\ Secondary\ Heat\ Pump\ Cost{+}Secondary\ Hot\ Thermal\ Stores{+}Secondary\ Cold\ Thermal\ Stores \tag{28}$$

$$CC{=}\quad CHP{,}PC\ {+}CHP{,}SC{+}\quad CTES{,}HC{+}CTES{,}CC \tag{29}$$

The primary heat pump cost is the capital investment of the heat pump which serves the primary energy center, $C_{HP,P}$. The secondary heat pump cost is the capital investment of the heat pump which serves the secondary energy center, $C_{HP,S}$. The secondary hot thermal store is the storage capacity for hot water within the secondary energy center, $C_{TES,H}$. The secondary cold thermal store is the storage capacity for chilled water within the secondary energy center, $C_{TES,C}$.

$$\mathit{Operating\ Cost}=\mathit{Primary\ Distribution\ Pumping\ Cost}+\mathit{Primary\ Heat\ Pump\ Electricity\ Cost}+\mathit{Secondary\ Heat\ Pump\ Electricity\ Cost} \quad [30]$$

$$CO=CdP,Pe,i+CHP,Pe,i+\ CHP,Se,i,j \quad [31]$$

The primary distribution pumping cost is electrical cost of pumping in the ambient loop at each time step, $C^{e,i}_{dP,P}$. The primary heat pump electricity cost is the cost of electricity at time step, i, which is used to power the primary heat pump, given by $C^{e,i}_{HP,P}$. The secondary heat pump electricity cost is the cost of electricity at time step, i, which is used to power heat pump, j, given by $C^{e,i}_{HP,P}$. The pumping cost in the secondary distribution loop is not considered the network operator’s responsibility, and therefore not considered here.

The cost of electricity is the units of electricity used at time step, i, multiplied by the unit cost of electricity at the same time step. This is given in 32 to 34.

$$C^{e,i}_{dP,P} = dP^{i} \times C^{e,i} \quad [32]$$

$$C^{e,i}_{HP,P} = Q^{i}_{W,P} \times C^{e,i} \quad [33]$$

$$C^{e,i,j}_{HP,S} = \ Q^{i,j}_{W,S} \times C^{e,i} \quad [34]$$

The unit cost of electricity is given by $C^{e,i}$. dP^{i} denotes the electricity for pumping, $Q^{i}_{W,P}$ and $Q^{i,j}_{W,S}$ denote the electricity used by the primary heat pump and secondary heat pumps, respectively.

6.2.3. Hydraulic modelling: Ambient Loop

The electrical energy used by the heat pumps will depend on the temperature of the ambient loop. This can be related through the Coefficient of Performance (COP). The relationship between the COP and electricity used is shown in 35 and 36. The COP is highly dependent on the difference in temperature between the source (ambient loop) and sink temperature (secondary distribution). The modelling approach of the COP is detailed in 6.3.5 below.

$$Q^{i}_{W,P} = \frac{Q^{i}_{HP,P,H}}{COP^{i}_{HP,P,H}} + \frac{Q^{i}_{HP,P,C}}{COP^{i}_{HP,P,C}} \qquad [35]$$

$$Q^{i,j}_{W,S} = \sum \frac{Q^{i,j}_{HP,S,SH}}{COP^{i,j}_{HP,S,SH}} + \sum \frac{Q^{i,j}_{HP,S,DHW}}{COP^{i,j}_{HP,S,DHW}} + \sum \frac{Q^{i,j}_{HP,S,C}}{COP^{i,j}_{HP,S,C}} \qquad [36]$$

The COP in the secondary system will vary depending on the demand temperature, and so distinct values for the space heat, domestic hot water, and space cooling are used. The primary heat pump is only used to maintain the ambient loop within boundary conditions and so only one COP is taken for the hot side COP and one for the cold side COP. These are calculated at every time step.

The ambient loop must be sized to provide the energy required to meet the demand. However, if the network is oversized the operator will suffer higher capital and operating costs through installation of oversized pipes in primary distribution (capex) and higher thermal losses (opex). A relation for the annual cost of the ambient loop per unit pipe length is given in 37.

$$C_{P,annual} = (C_1 + C_2) \cdot a + C_{e,mean} \frac{\tau}{\eta} \frac{\Delta P_{Max}}{L} \cdot \dot{V} \qquad [37]$$

The annual cost of the ambient loop is given by $C_{P,annual}$. C_1 and C_2 are constants based on the cost of pipework. a is the annuity factor used to calculate present value of the pipework. $C_{e,mean}$ is the average annual unit cost of electricity. τ is the time period of analysis, in this case 1 year. η is the pump efficiency, ΔP_{Max} is the maximum design pressure. The length of the network is given by L, and the volumetric flow rate is $\dot{V}$.

The optimal size must be based on maintaining a minimum pressure in the network for the user furthest from the primary energy center, but also to be able to deliver peak requirements. Where the heat network is only used to meet the base demand, the minimum pressure should be used. In the scenario presented here, there are no top up boilers and so peak demand must be met from the ambient loop. The pressure drop is given in 38.

$$\frac{\Delta P_{Max}}{L} = \frac{\lambda}{d}\frac{1}{2}\rho v^2 \qquad [38]$$

d is the internal diameter of the pipe, ρ is the fluid density, v is the flow velocity at peak demand. The flow velocity is related to the volumetric flow rate and pipe diameter by 39

$$v = \frac{4}{\pi}\frac{\dot{V}}{d^2} \qquad [39]$$

Equation 38 can be combined with Equation 39 to give Equation 40.

$$\frac{\Delta P_{Max}}{L} = \lambda\rho\frac{8}{\pi^2}\frac{\dot{V}^2}{d^2} \qquad [40]$$

Equation 40 is substituted into Equation 37 to Equation 41. Equation 41 is derived with respect to the inner diameter to give Equation 42. By setting Equation 42 equal to zero, the minimum pipe diameter can be found from Equation 43

$$C_{P,annual} = (C_1 + C_2) \cdot a + C_{e,mean} \frac{\tau}{\eta} \left(\lambda \rho \frac{8}{\pi^2} \frac{\dot{V}^2}{d^2} \right) \cdot \dot{V} \tag{41}$$

$$\frac{d \;\; C_{P,annual}}{d \;\; (d)} = C_2 a - C_{e,mean} \lambda \rho \frac{\tau}{\eta} \frac{40}{\pi^2} \frac{\dot{V}^2}{d^6} \tag{42}$$

$$\frac{d \;\; C_{P,annual}}{d \;\; (d)} = 0$$

$$d = \left(\frac{40}{\pi^2} \lambda \rho \frac{\tau}{\eta} \frac{C_{e,mean}}{a C_2} \right)^{\frac{1}{6}} \cdot \dot{V}^{\frac{1}{2}} \tag{43}$$

6.2.4. Hydraulic Modelling: Secondary Distribution

The secondary distribution loop is considered to be outside the scope of this study. For the purpose of this study, the secondary energy center is designed to supply the secondary distribution loop with energy to heat or cool the secondary loop to the required temperature. The customer is charged for the energy delivered through a unit charge, and is charged a daily standing rate to cover the cost of the ambient loop. This is the primary revenue stream to the operator and described in Equation 44.

$$C_{rev} = N C_{Stand} + \sum \left(Q^{i,j}_{HP,S,SH} + Q^{i,j}_{HP,S,DHW} + Q^{i,j}_{HP,S,C} \right) C_{mark} C^{e,i} \tag{44}$$

The total revenue is C_{rev}, the number of customers on the network is N, the standing charge is C_{Stand}, and the markup percent is C_{mark}.

6.2.5. Optimisation Objective Function

The lifecycle cost benefit is assessed on the Net Present Value (NPV). This becomes the optimization objective, shown in Equation 45.

$$Max\ \ NPV = max \sum_{n=0}^{n=25} \frac{C_{rev} - C^{O}}{(1+r)^{n}} + C^{C} \qquad [45]$$

6.2.6. Energy Balance

At each time step, each heat pump must meet the respective demand, illustrated by 46 to 48. The demand is formulated as an inequality rather than an equality to give greater freedom to the operating response e.g. could the heat pump of customer A be intentionally controlled to support the COP of customer B's heat pump.

$$Q_{dem,S,SH}^{i,j} \leq Q_{HP,S,SH}^{i,j} \qquad [46]$$

$$Q_{dem,S,DHW}^{i,j} \leq Q_{HP,S,DHW}^{i,j} \qquad [47]$$

$$Q_{dem,S,C}^{i,j} \leq Q_{HP,S,C}^{i,j} \qquad [48]$$

Each heat pump will absorb or reject energy from/to the ambient loop to meet the required demand. The amount of energy which is required to be absorbed depends on the COP.

$$Q^{i,j}_{HP,S,SH} = COP^{i,j}_{HP,S,SH} \times Q^{i,j}_{abs,S,SH} \quad [49]$$

$$Q^{i,j}_{HP,S,DHW} = COP^{i,j}_{HP,S,DHW} \times Q^{i,j}_{abs,S,DHW} \quad [50]$$

$$Q^{i,j}_{HP,S,C} = COP^{i,j}_{HP,S,C} \times Q^{i,j}_{rej,S,C} \quad [51]$$

The net energy exchange with the ambient loop will change the temperature of the loop such that 52-55 holds true.

$$T^{i,j}_{loop} = T^{i-1,j}_{loop} + \Delta T^{i,j}_{loop,HP} + \Delta T^{i,j}_{loop,losses} \quad [52]$$

$$\Delta T^{i,j}_{loop,losses} = \frac{\frac{A}{L} \cdot k \cdot \Delta T^{i,j}_{loop,ground}}{\dot{m}c_p} = \frac{\pi \cdot d \cdot k \cdot \Delta T^{i,j}_{loop,ground}}{\dot{m}c_p} \quad [53]$$

$$\begin{aligned} T^{i,j}_{loop} = T^{i-1,j}_{loop} &- \frac{Q^{i,j}_{abs,S,SH} + Q^{i,j}_{abs,S,DHW} - Q^{i,j}_{rej,S,C}}{\dot{m}c_p} \\ &- \frac{\pi \cdot d \cdot k \cdot \Delta T^{i,j}_{loop,ground}}{\dot{m}c_p} \end{aligned} \quad [54]$$

$$subject\ \ to\ \ 10°C \leq T^{i,j}_{loop} \leq 40°C \quad [55]$$

$T^{i,j}_{loop}$ is the temperature of the ambient loop at time i, position j. $\Delta T^{i,j}_{loop}$is the change in ambient loop temperature at time i, position j. $T^{i-1,j}_{loop}$ is the ambient loop temperature at the previous time step. $\Delta T^{i,j}_{loop,losses}$ is the ambient loop temperature change caused by thermal losses from the primary distribution pipe. $\dot{m}$ is the mass flow rate in the ambient loop, and c_p is the specific heat of water (the carrier fluid in ambient loop). $\frac{A}{L}$ is the ratio of pipe surface area to length. k is the thermal conductivity of the carrier pipe.

6.3. Methods

6.3.1. Building Energy Demands

Four building energy models were created in IES VE and used to generate indicative space heating, hot water, and space cooling demands. The geometries were based on architectural drawings for four different building types. Space conditioning demands are primarily driven by external air temperature, internal thermal gains, and building constructions. These are summarized below.

6.3.2. External Temperature/Weather File

The UK Meteorological Office gathers data from weather stations across the UK. The external temperature is modelled from a weather file. The gathered data is used to produce Design Summer Year (DSY) weather files, which can be used as predictive weather files under varying degrees of global warming. The methodology is described extensively here. The weather file chosen is London Weather Centre (LWC) Design Summer Year 2050 50th percentile. The key data from this is the wet bulb temperature of external air, shown in Figure 6.2 This weather file has been chosen as it is an industry accepted prediction of weather conditions in 2050.

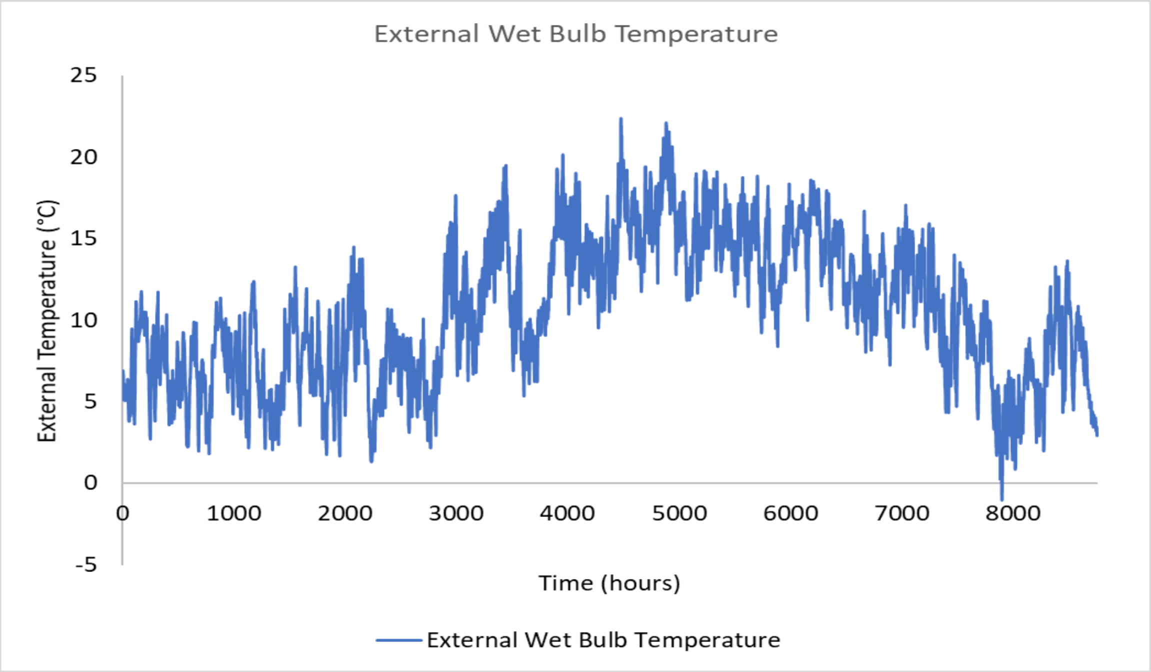

Figure 6-2 External air wet bulb temperature taken from London Weather Center Design Summer Year 2050 50th percentile.

6.3.3. Internal Thermal Gains

The internal thermal gains of a space is the sensible or latent heat added to an internal space (room). This is split into occupancy gains (heat from people), lighting gains, and equipment gains (everything other than people and lights). Occupancy gains can be difficult to assign accurately, as the heat emitted by a person depends on a large number of conditions (activity, clothing level, thermal comfort etc.). Industry best practice has been used to assign rational values for these gains, summarized in Table 6.1.

Table 6.1 Example of Internal thermal gains used in modelling.

Gain Type	Latent	Sensible	Total
People (W/person)	60	90	150
Equipment (W/m^2)		40	40
Lighting (W/m$^{2)}$		35	35

6.3.4. Building Constructions

The materials used in construction will have significant impact on the energy demand of each building. These are summarized in Table 2. The values presented here were the target values of the building design team prior to construction.

Table 6.2 Summary of construction values used in IES VE to produce thermal demands.

Construction Type	**Hotel**	**Office**	**Residential**	**Retail**
	Thermal Conductivity (W/m^2.K)			
External Wall	0.18	0.25	0.13	0.30
External Glazing	1.4 (G-Value 0.40)	1.40 (G-Value 0.33)	1.4 (G-Value 0.5)	1.80 (G-Value 0.68)
Exposed Floor	0.20	0.20	0.13	0.45
Exposed Roof	0.15	0.2	0.13	0.25

Table 6.3 Summary of modelled building energy demands showing floor normalized space heating, domestic hot water, and space cooling demand.

Usage Type	Floor Area (m^2)	Annual Heating (kWh/m^2)	Annual Space Cooling (kWh/m^2)
Hotel	17’797	75	25
Office	27’250	33	32
Residential	24’402	66	-
Retail	12’026	5	78

No cooling load has been calculated for the residential case. It is likely many residential developments will exceed the comfortable temperature limits in warmer months. However, very few dwellings in moderate climates are fitted with air conditioning. It is expected that any comfort cooling in dwellings can be achieved through ventilation strategies and passive measures. Figure 6.3 shows the annual hourly demands.

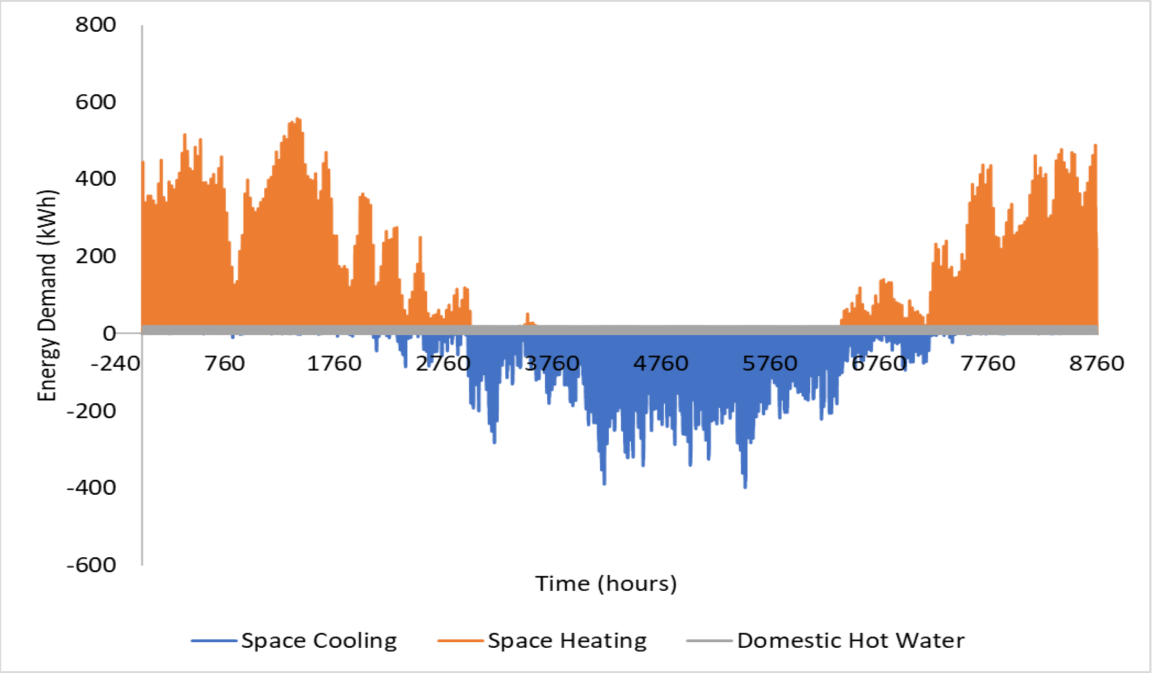

Figure 6-3 Plots of annual energy load profiles for each building usage type, showing space heating (orange), domestic hot water (grey), and space cooling demand (blue). Hourly data is plotted, taken from a dynamic simulation using IES VE. The temperature of demand is incorporated into the demand profile.

6.3.5. *Heat Pump Modelling*

Common heat pumps use electricity to efficiently move thermal energy from a cold source (ambient loop) to a warmer sink (secondary loop). As the temperature difference between the source and sink increase, the performance of the heat pump decreases. The performance of a heat pump is known as the Coefficient of Performance (COP).

It was assumed that heat pumps are used to absorb and reject heat from the ambient loop and that the heat pump is directly connected to the ambient loop, with no intermediate heat exchanger. It should be noted that in practice it is much more likely that an intermediate heat exchanger would be used to protect the secondary side from pressure surges in the main network.

The heat pumps are modelled with variable speed compressors to modulate to meet the end user demand. The performance of a heat pump will vary under partial load (i.e. if the heat pump operates below the design capacity) and so modelling was used to account for the variation in performance. Published data was used to model four different heat pumps, which were sized to meet the entire heating and hot water demand.

There are very few reversible water source heat pumps on the market with published performance data. For this reason, the heat pumps and chillers which were modelled for the performance relationships were single directional. The cooling performance of the single directional chiller was assumed to be the same as the cooling performance of the reversible heat pump in cooling mode. This is acknowledged as a limitation in the study.

Details of the heat pump linear regression being modelled is given in Figure 6.4.

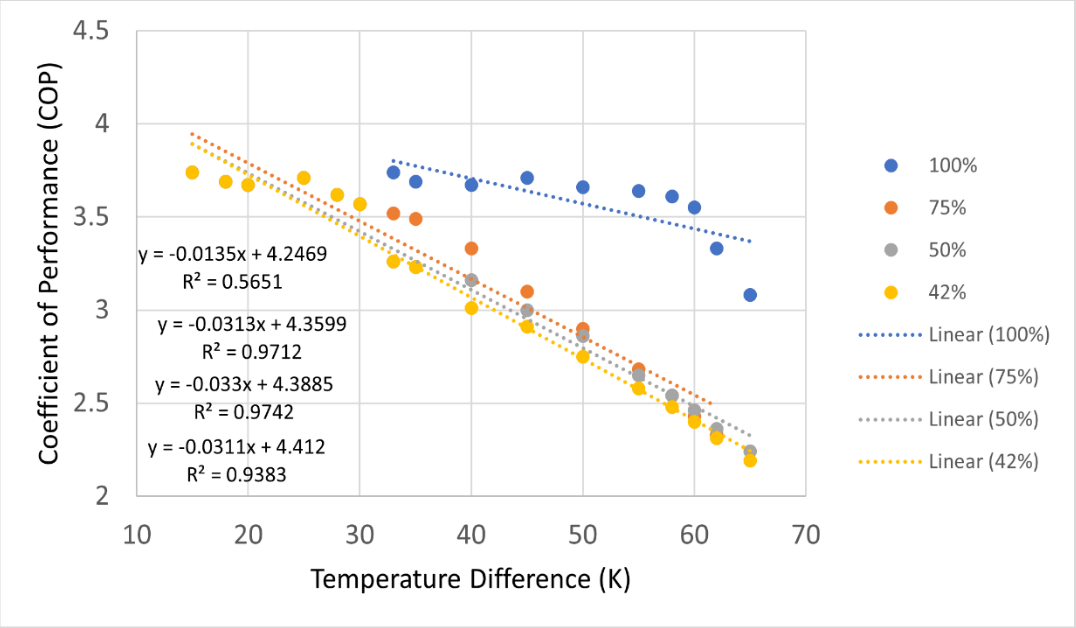

Figure 6-4 Linear regression analysis of published heat pump performance data, using COP and temperature difference. Data sets are shown for performance at varying percentage of peak capacity.

Figure 6.4 shows the COP increasing from 42% load to 100% load at equivalent temperature differences. Below 100% load, the difference between performance at 42% and 75% load is small and has a good linear approximation with temperature difference. Additionally, the ambient loop can only operate between 10°C and 40°C. The highest temperature demand is 60°C, giving a maximum heating temperature difference of 50°C, and a minimum of 20°C.[4]

As the system uses a water-water heat pump, it is assumed that chilled water is provided to the secondary system to be used in terminal air conditioning (e.g. chilled beam, local air handling units etc.). Chilled water is provided at 5°C, giving a maximum temperature difference of 35°C and a minimum temperature difference of 5°C.

As no data is available for the performance between 75% and 100%, a linear interpolation was used.

The heat pump is modelled to operate within the range 42% to 100% load.

6.4. Results

This section presents the results of the study.

6.4.1. Building Energy Usage

It is important to understand the building energy usage which is connected to the ambient loop to be able to fully understand the dynamics of the system. The demand of each building type is shown in Figure 6.5. Figure 6.5 shows that the four building types have significantly different annual demand composition. The retail space is largely dominated by space cooling, while residential is completely heating.

Figure 6 shows the annual heating and cooling demand profiles for each building type. In this figure, heat is inclusive of space heat and domestic hot water. As expected, the cooling demand is significantly higher in the summer and lower in the winter. The heating demand is higher in winter and lower in summer. While this may seem obvious, it is important to understand to appreciate the dynamics of the system. From Figure 6.5, it may

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[4] The figure clearly shows that the overall relationship between COP and temperature difference is not completely linear. However, significant sections of the operating range are linear and show good approximation, which is why the heat pumps were controlled to operate within this range (approx. 42-75% load).

be initially assumed that the potential for energy sharing between retail space and residential may be very high as they have almost opposite annual demands (i.e. retail has high cooling demand, residential has high heating demand), but from Figure 6.6 it can be seen that there is a time difference between the retail cooling demand and the residential heating demand (only approximately 6% of demands have simultaneous loads). For all four building types, the simultaneous load is approximately 10%.

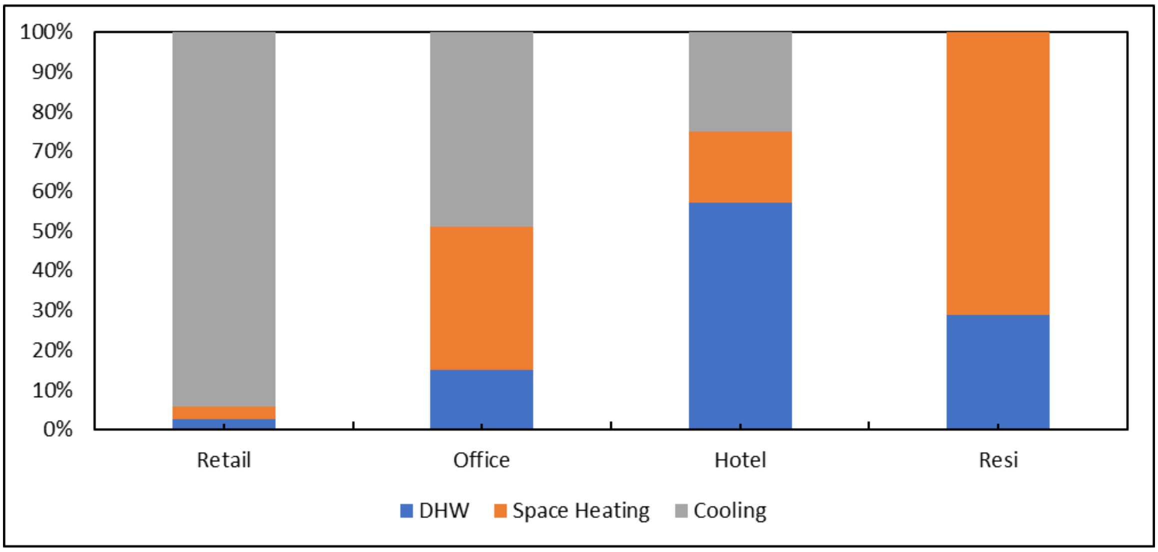

Figure 6-5 Percentage composition of the modelled building energy demands for the buildings connected to the ambient loop.

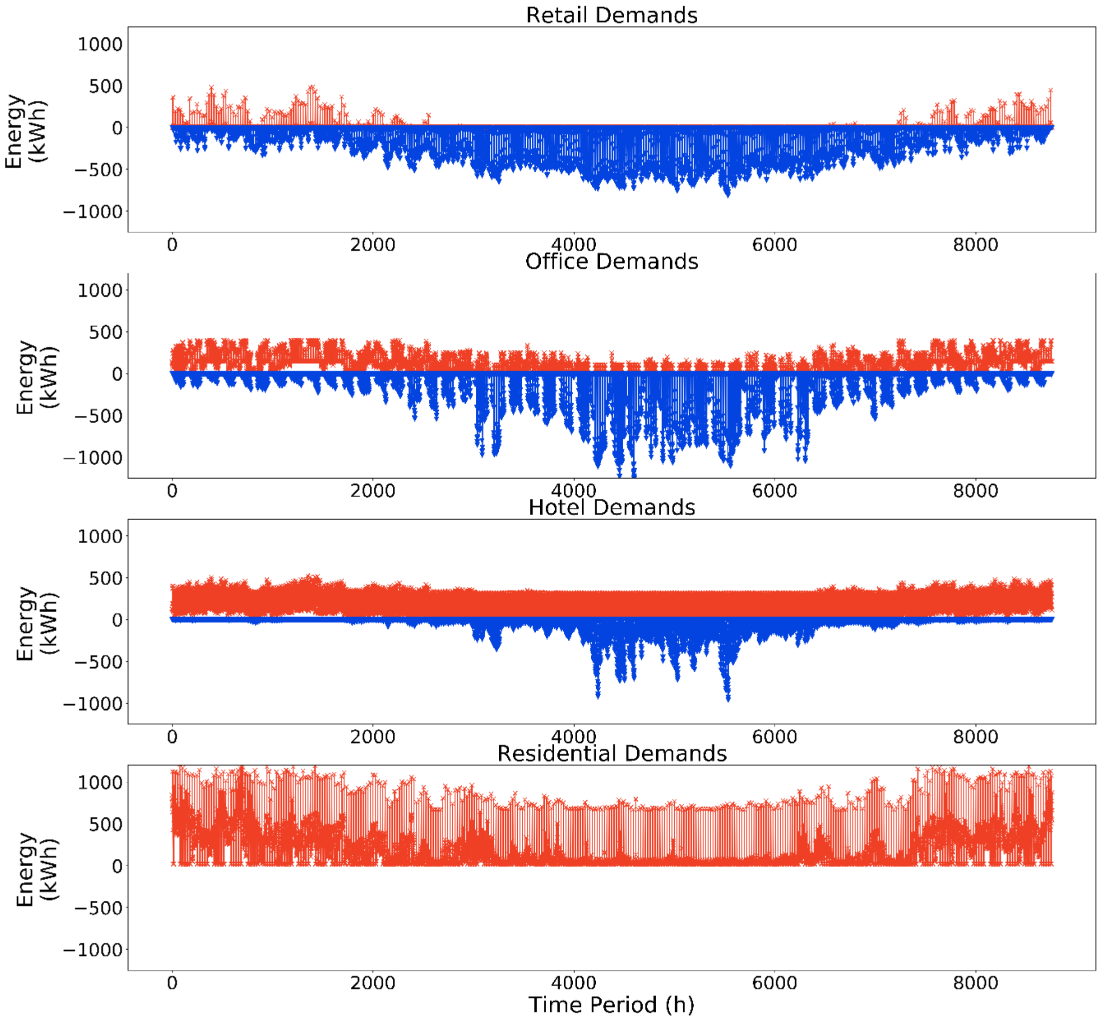

Figure 6-6 Heating and Cooling profiles for the four modelled building types.

The ratio of simultaneous load will change across the seasons, which can lead to seasonal variations in performance. A sample day is shown for the network in Figure 6.7. This shows the heating, cooling, and resultant load on the network across a sample spring, summer, and winter day. From Figure 6.7, there is significant time gap between complimentary demands, which supports the need for thermal storage – both over short time horizons (e.g. daily) and long time horizons (e.g. seasonal).

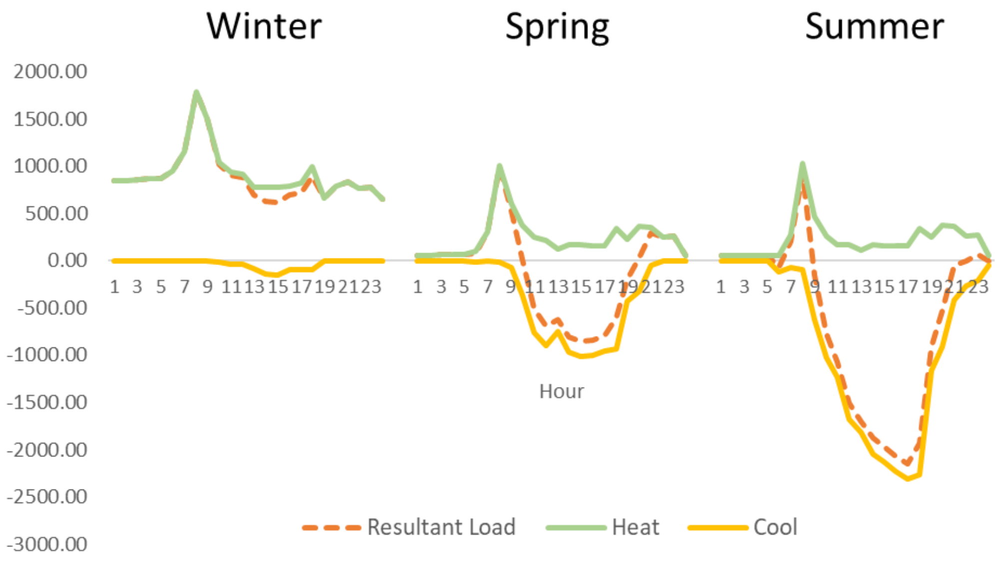

Figure 6-7 Heating, Cooling, and theoretical resultant load profiles of network on sample days across different seasons.

6.4.2. Temperature and Flow

The optimal temperature and flow will vary from season to season as the demand shift. In a traditional network, pressure control and temperature control are used daily and seasonally to minimize the thermal loss from the network. However, a thermal energy sharing network has the added value of improving neighboring heat pump efficiency based on the rejected energy from other users on the network.

Figure 8 shows how the heat pump COP of each use case varies depending on the source temperature (shown diagrammatically in Figure 6.9). In this scenario, the hotel is modelled as being at the start of the network, followed by retail, then office, and residential at the end of the network. The hotel heating performance is improved by being at the start of the network compared with other users. This is because the inlet to the network is assumed to be maintained at the set point. The hotel has a significant heating demand(shown in Figure 6.5), and therefore absorbs heat from the network causing the network temperature to drop immediately before the inlet to the retail building. This is noted from the drop in heating COP for the retail building. However the same effect is not seen in the office space, which immediately follows the retail space in the simulation. This is because the retail space is almost exclusively space cooled, with very little heating demand (90% space cooling). The retail space therefore rejects heat to the network which causes the temperature of the network to rise. The rise in temperature benefits the space heating performance of the office building, giving a slightly higher average heating performance for the office space than the retail space.

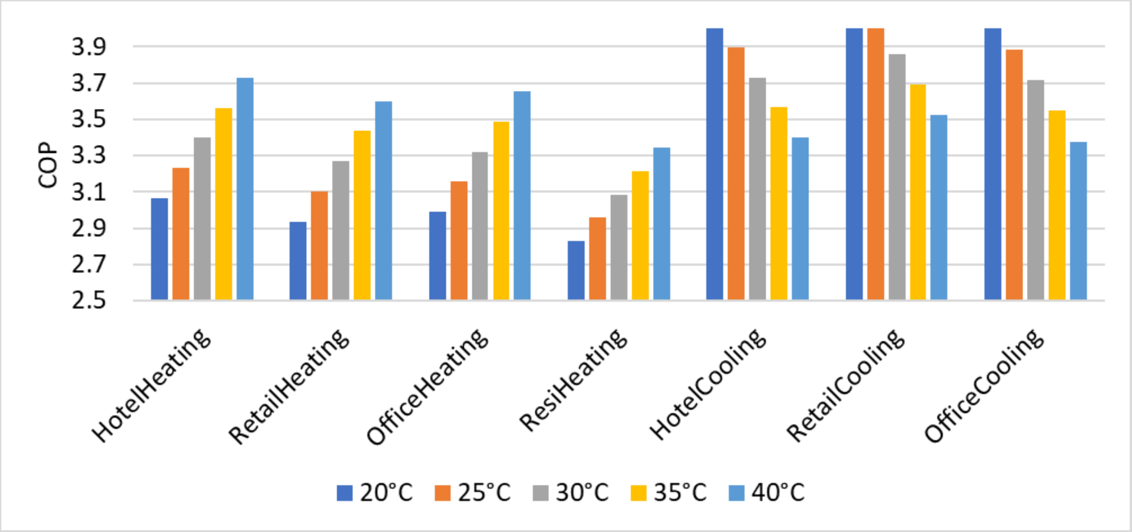

Figure 6-8 Average Annual COP for each simulated building type. No residential cooling is modelled.

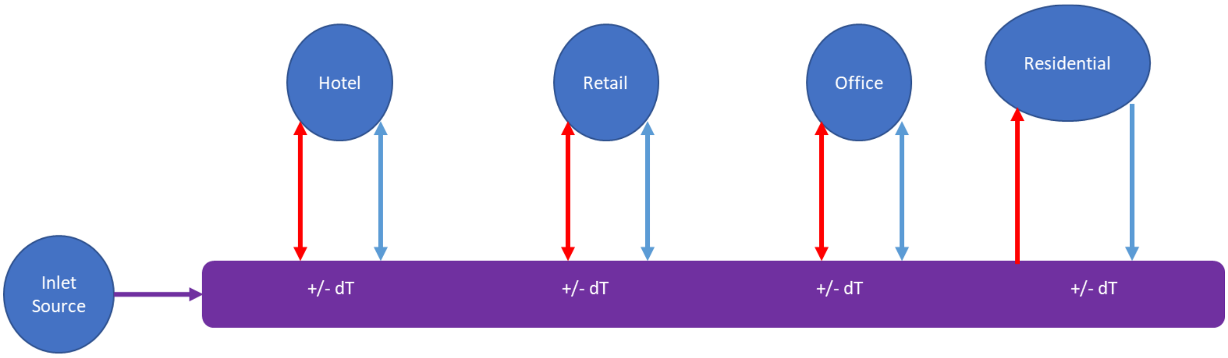

Figure 6-9 Diagram of modelled simulation. Each set of heating and cooling demand is connected to the ambient loop. Accepting/rejecting energy causes a temperature changed for the ambient loop (dT). The inlet source remains constant throughout the simulation.

In all scenarios, the residential heating performance is lower than the other building types. In this scenario, the residential building is at the end of the network. The total annual demand on the network has a greater heating demand than cooling demand (Total heating: 3.9GWh, Total Cooling: 2.3GWh) and therefore a net reduction in the pipe temperature is expected. This is shown in Figure 10. The temperature difference across the residential demand is typically higher than for the other building types (typically 10°C). This is, first, because the residential heating demand is greater than the other building types. The second reason is that the residential demand is modelled without space cooling. Space cooling in the other building uses offsets some of the temperature drop from the heating demand. It can therefore be concluded that the residential demand can only cause a net decrease in ambient loop temperature, and as such would benefit being placed either immediately after a large cooling demand (e.g. retail space) to improve the residential heating COP or placed immediately before a large cooling demand to improve the cooling COP.

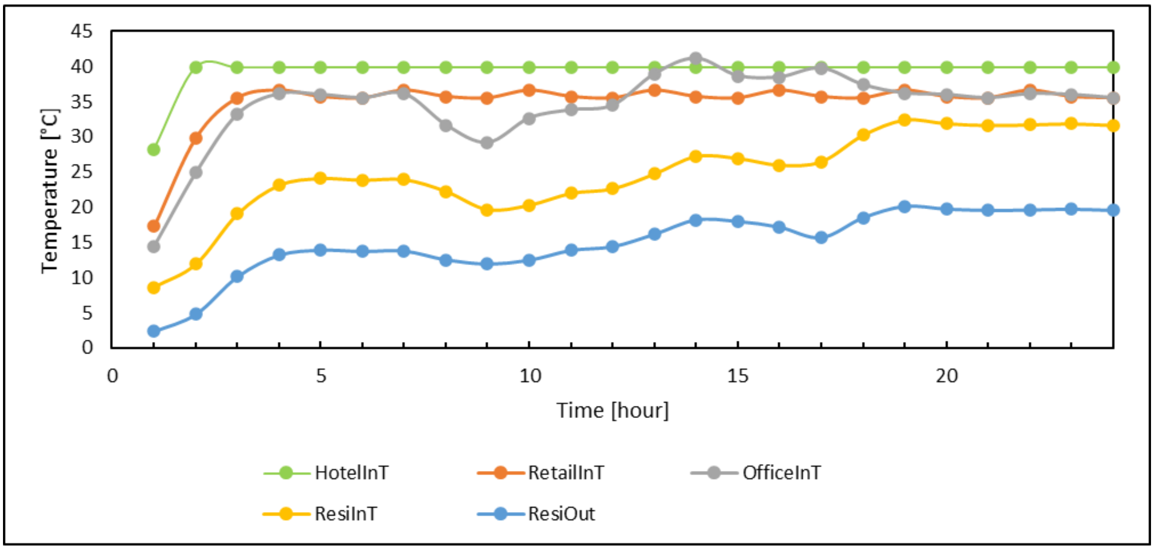

Figure 6-10 Ambient loop temperature at each building interface for an example day.

Figure 6.11 shows the average pipe temperature across the year (red) when compared with the composition of heating and cooling demand. In the summer, the average temperature increases as more cooling is required (therefore rejecting heat to the pipe). In the winter, the temperature drops as more heating is required. In the simulation, the pipe temperature was prevented from dropping below 5°C. However, for the given flowrate (1000kg/hour) the ambient loop can fully manage its own temperature with a steady inlet flow of water at a constant 40°C. However, as the flowrate drops the required energy causes a greater temperature change. This is shown by the change in COP in Figure 6.12.

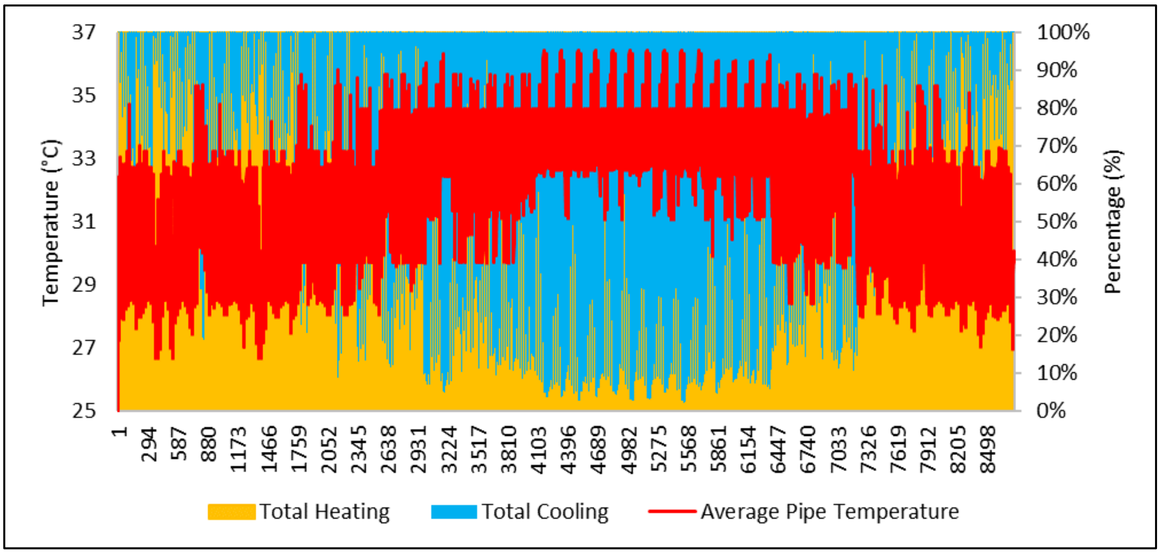

Figure 6-11 The average pipe temperature (left Y-axis) shown with the percentage composition of heating and cooling demand (right Y-axis).

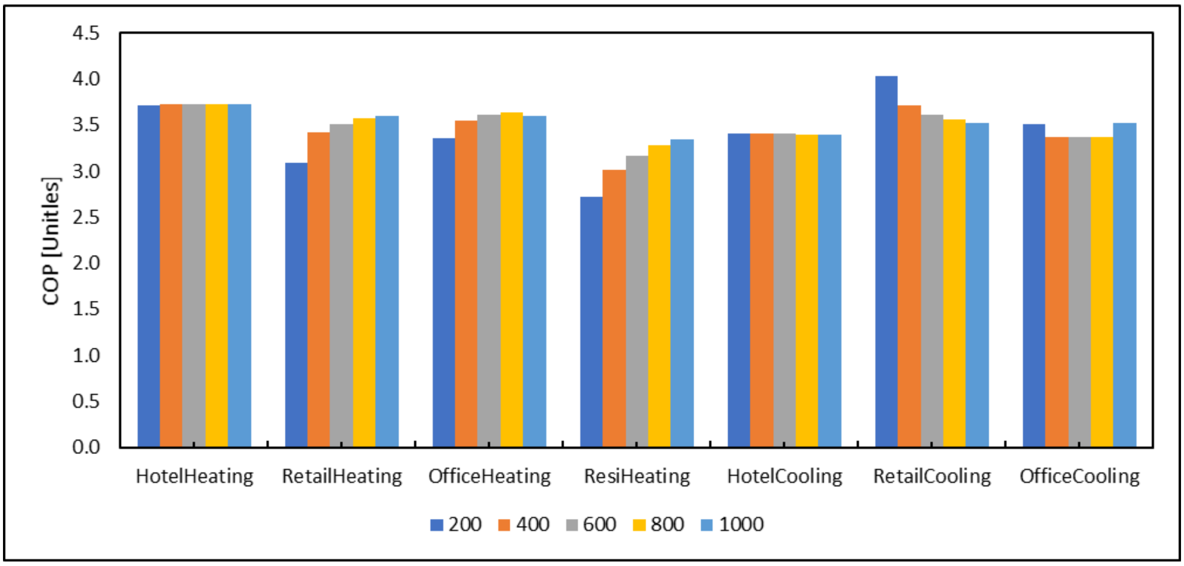

Figure 6-12 COP summary for variable flow rates (kg/hour). The inlet temperature is maintained at 40°C.

From Figure 6.12, the hotel heating and cooling COP is not affected by the flow rate. This is because the hotel demand is placed at the beginning of the network in this scenario and therefore the inlet temperature is constant at 40°C for all cases. The heating COPs are shown to increase as the flowrate increases. This is because the temperature remains closer to the inlet at higher flowrates i.e. a smaller portion of the available energy is absorbed or rejected as the flowrate increases. This is to be expected. However, it is interesting that the cooling efficiency is higher at low flow rates than high flowrates. Even at low space heating demands, the buildings require domestic hot water. This heat is required simultaneously with the cooling. At low flowrates, the DHW demand has a bigger impact on the temperature of the network than at high flowrates, therefore giving an improvement in the cooling efficiency. From this, it can be concluded that there is year round added value from thermal energy sharing, even in the absence of thermal storage.

6.4.3. Demand Density

In traditional heat networks (e.g. 3G/4G networks without energy sharing) the linear demand density is often used as indicator of financial viability. This is because as the demand density increases, the thermal losses (and therefore lost revenue) reduces in proportion to the energy sales i.e. more energy is sold with roughly the same absolute losses. However, this has not been discussed in detail for thermal energy sharing networks.

Figure 6.13 shows the energy consumption for varying demand densities for an energy sharing network. The change in power consumption for each user is negligible (<1% variance for most cases). This can be understood from considering Figure 6.14 which shows the average ambient loop temperature for the network across varying demand densities on a sample day. From the figure, the largest difference is in the change from 20m distance between buildings to 40m distance between buildings. This is because proportionally, this is the largest jump i.e. from 20m to 40m the network doubles, thereafter the increase in network length is diminishing proportionally. As the network length increases, the network temperature moves closer to the ambient ground temperature (approximately 10°C in this case). The network is controlled such that the loop does not drop below 10°C or go above 40°C. In this example, no energy is required to prevent the loop exceeding the upper limit, however as the network length increases, the energy required to maintain the loop above the lower set point increases. This is due to the composition of demands on the network. It is expected that varying these demands will influence the required energy to maintain the upper and lower limits of the network.

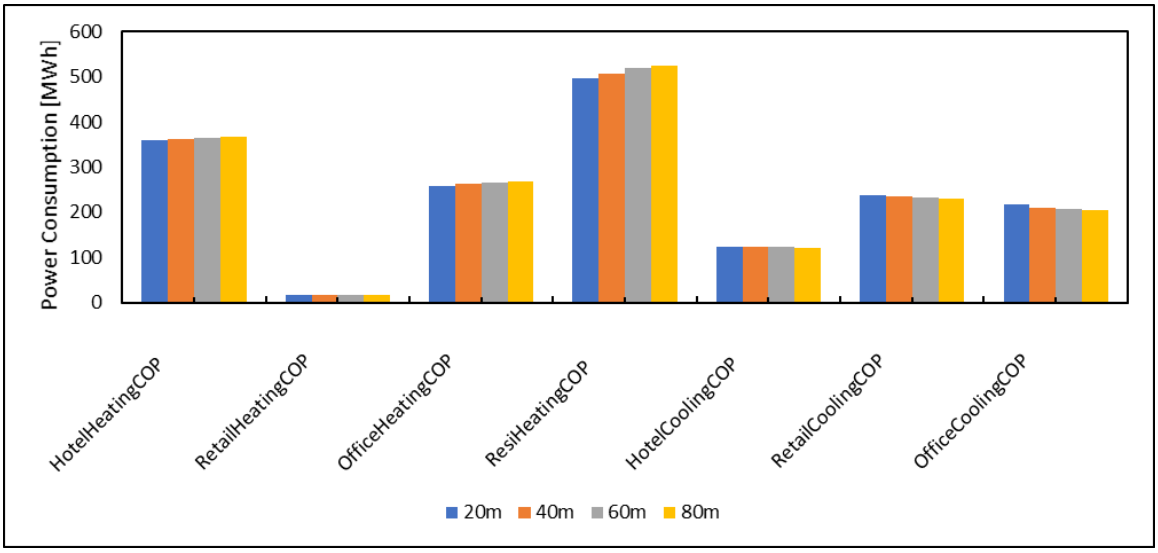

Figure 6-13 Power consumption of users connected to the network under varying distances between buildings.

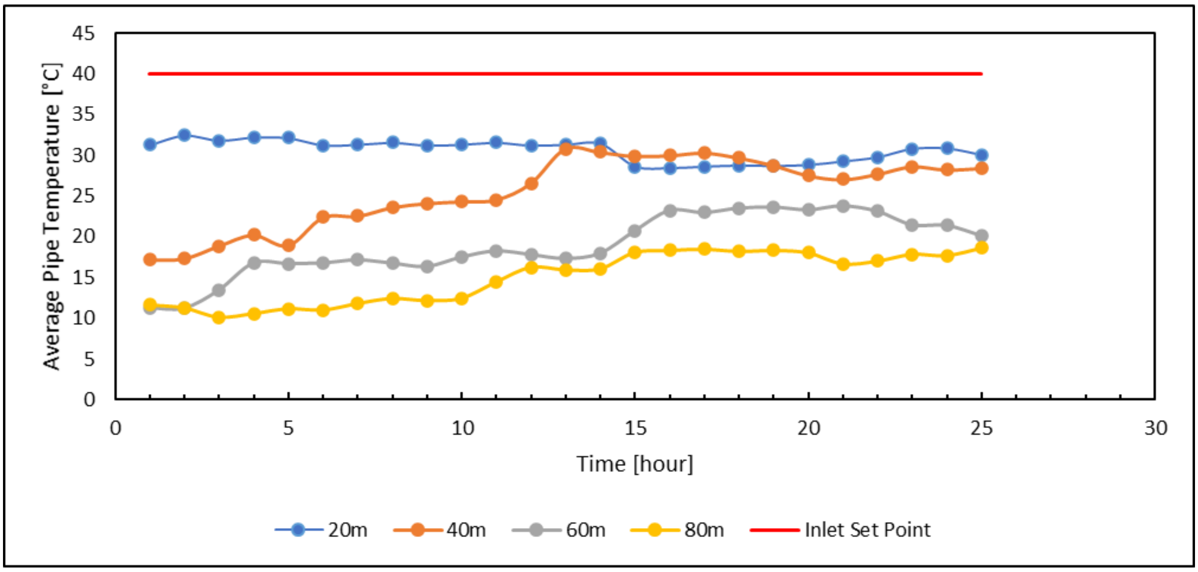

Figure 6-14 Average ambient loop temperature for varying distances between buildings.

Figure 6.15 shows the demand density on the modelled network for increasing network length. Although the demand density decreases with network length, the increase in energy consumption is marginal; this is much lower than would be expected from a traditional heat network. This is partly because the ambient loop operate at much lower temperatures (40°C for the ambient loop compared with circa. 70°C for 3rd generation heat networks). This shows a significant advantage of energy sharing networks compared with non-sharing networks; the demand density is not a defining factor on efficiency, particularly at long network lengths. However, the economic implications should still be considered.

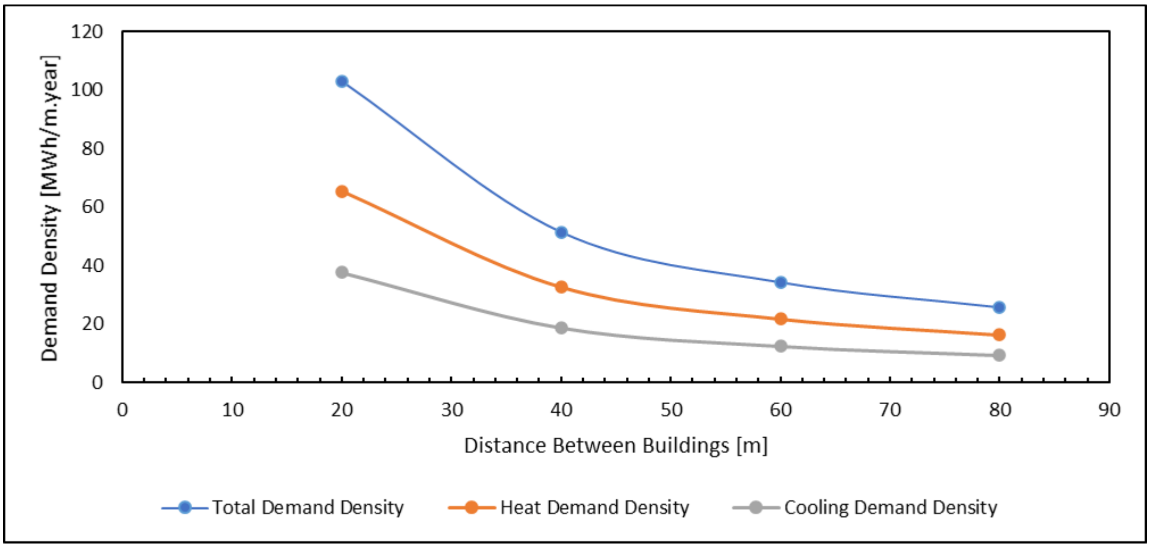

Figure 6-15 The demand density shown against the distance between each building.

6.5. Conclusions

The aim of this paper has been to identify through dynamic modelling and optimization the routes to improving the energetic benefit of a thermal energy sharing network. The flow temperature has been shown to have significant impact on both heating and cooling, which is to be expected. However, it has been shown for the first time that variable flow control can offer improvements to the heat pump performance with negligible energetic cost i.e. by reducing the flowrate, it is possible to selectively improve the heat pump performance due to a greater shift in network temperature at lower flow caused by the demands on the network. Energy efficiency improvements have been noticed in traditional heat networks at low flow rates, but for different reasons i.e. reduction in thermal losses.

It has been identified for the first time that load placement on the network can have significant benefits, if chosen correctly. Co-locating buildings with high but complimentary load profiles can offer significant improvement in energy efficiency and COP improvement.

It is acknowledged that there are limitations to the work presented. The first is that thermal storage has not been considered. We have addressed this in another paper, however future work would benefit from assessing this through dynamic modelling. The window of opportunity to make use of the findings in this paper is relatively small. The work targets system design stages, where there is flexibility in load placement, but it is acknowledged that architectural and planning constraints may limit the flexibility of load placement.

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7. Summary and Conclusions

7.1. Summary of Research Aims

Energy networks are complicated. Heat networks aim to offer a “one size fits all” approach to providing heat to multiple end users, but as has been shown, this is difficult to do economically. Heat networks are designed to last, which has made 2nd and 3rd generation networks a significant and long term issue when decarbonisation is pursued. Building standards are being tightened year on year, so perhaps new buildings will reach a plateau of low energy usage, suitable to be connected thermally with minimal losses and minimal capital. However, retrofit is very likely to become the block in the road to mass rollout of heat networks.

Heat networks were largely overlooked in the UK for a long time. Various political and social factors meant heat networks were largely redundant for a UK market. For heat networks to be successfully deployed in the UK, it is critical to assess why they were unsuccessful in the past. The aim of Chapter 2 was to explain this. While Chapter 2 focused on historic challenges with heat networks, Chapter 3 aimed to look ahead and address the roadblocks to low temperature (4GDHNs).

The conclusions of Chapter 2 and Chapter 3 pointed heavily to retrofit applications as the source of most problems in a heat network. Although it wasn’t the original intention, the aims of this body of work became focused primarily on retrofit applications. Governments in the UK and abroad have placed focus on expanding district heating networks, which seems to be almost blind to the challenges of retrofit. Chapter 4 sought to describe a methodology and case study for demonstrating the limitations of a 3rd generation heat network and a 4th generation low temperature heat network in the context of existing heat emitters and infrastructure. The chapter focused specifically on a water source heat pump heat network, as this was particularly prominent in local media and national interest.

The work from Chapter 4 naturally led to the work in Chapter 5. The conclusions from Chapter 4 showed the current market limitations of heat pumps. Much of this limitation comes from the maximum supply temperature a heat pump can currently provide, and the high thermal losses caused by this high temperature. If Chapter 4 is summarized by the question “Why do heat networks not work for retrofit applications?” then Chapter 5 would be “How do we make heat networks work for retrofit applications?”. Chapter 5 investigated energy sharing networks as a solution to retrofit problems. By distributing at low temperatures and upgrading at a local substation, energy savings could in theory be made over high temperature distribution. Additionally, by having a single low temperature network connecting multiple reversible heat pump units, the potential to share thermal energy becomes possible. Chapter 5 sought to demonstrate the economic, energetic, and carbon savings of such a system. The primary ambition for this chapter was to create data which could be utilized within industrial applications.

Chapter 6 focused on the detailed and dynamic optimization of Chapter 5 and addressed the shortcomings of the original model. This focused on understanding the complicated dynamics of temperature and pressure on a thermal energy sharing system. This work identified the relevance of traditional metrics (e.g. linear demand density) on lower temperature ambient loop networks.

7.2. Summary of Novel Contributions and Conclusions

This thesis focused on the challenges and solutions to operating high efficiency district heating networks. The key novel contributions of the work are presented below.

1) **Identification of lowest supply temperature in a heat network for retrofit applications.**

The critical challenge for retrofit application heat networks is in finding a supply temperature which is high enough to allow good heat transfer from the end user radiator to the space to be heated. Assuming a low carbon technology is capable of providing the required temperature (no lower than circa. 65°C), the problem becomes how to balance a heat network to match the new flow and pressure constraints. At this stage pumps may need to be swapped to a greater duty to create the needed rate of heat transfer. An additional caveat is that this route is almost impossible when a direct connection has been utilized within the network. This is only the network constraints, before any work has been done to allow the end user to operate at a lower temperature. The work in Chapter 4 showed that it is incredibly difficult to achieve thermal comfort within the chosen case study at temperatures below 85°C. It is currently not possible to achieve this with the renewable technologies available on the market.

2) Identification of the impact of minor refurbishment on supply temperature requirements for domestic dwellings

The work in Chapter 4 showed the value of minor refurbishments (approx. 30% energy usage reduction), and a river source heat pump (70% energy reduction). These are impressive numbers, but again limited by non-technical constraints. The cost of refurbishments is likely to be the largest inhibitor to low temperature heat networks in retrofit buildings. Only with high levels of insulation and double glazing can the supply temperature be dropped low enough to allow meaningful reduction in the heat network supply temperature. This is a serious inhibitor to retrofit heat network roll out.

3) Framework development for assessing the economic feasibility of 5th generation energy sharing networks

Thermal energy sharing networks have not been well documented in literature. Although some sources may claim these systems are already widely adopted, there is clear confusion amongst industry and academia as to the status and characteristics of a “5th generation” energy network. While Chapter 3 discusses the definitions of “ambient loops” in the context of the popular *Lund* definition of heat networks, Chapter 5 details this quantitively. A full system energy balance is presented as one of the first in literature to focus on thermal energy sharing, which is then adopted as a dispatch optimization. Most importantly, roles within the network are apportioned i.e. who owns the network, revenue streams etc. This is incredibly important in understanding and apportioning the overall carbon or financial value.

4) Provide a comparative analysis of technical metrics between traditional heat networks and energy sharing networks

Heat networks have not been widely adopted within the UK. It is therefore crucially important to understand the implications of introducing a new form of heat network to the market. This can be understood through comparison of traditional metrics (e.g. diversity, linear heat demand density). For the first time, it was shown that thermal energy sharing on its own offers very little improvement in diversity, carbon savings, cost, or energy when compared with the equivalent non-energy sharing network. However, when the ambient loop network is combined with ample thermal storage, there can be significant savings across all these metrics.

5) Identify the significance of tariff structure on energy sharing networks and demand response strategy

As discussed, the energy sharing network on its own offers very little improvement over the non-energy sharing network. However, it was shown that using thermal storage with a cost incentive (i.e. time of use tariff) can significantly change the operating strategy of a thermal energy sharing network and reduce peak power requirements on the local electrical network infrastructure. This goal is a priority area for the future in creating a resilient power network that can cope with the demands of electrified heat. For some scenarios, the diversity was as low as 28% on the heating side. This may be a huge improvement for local power networks, but comes with the risk of being 69% more expensive for the end user if no demand side management controls are in place.

Where a carbon levy was applied, it was significantly too low to force a change in operating strategy. This is a recurring theme in literature, which has yet to be addressed by government bodies. Until such a time, it is unlikely that end users will adopt lower carbon approach to using power.

6) Identify the role of building types in utilizing thermal energy sharing

In deciding if thermal energy sharing is worthwhile, the energy demand profiles are critically important (albeit with reducing significance as storage capacity increases). Some building types have been shown to be inherently better at sharing energy than other combinations. Connecting complimentary demand profiles could show a 14% increase in utilized shared energy. Inversely, some have been shown to be detrimental to energy sharing such as residential dwellings. This is primarily due to the lack of infrastructure in retrofit applications to transfer thermal energy between users i.e. non-domestic users will have a centralized heat pump, while residential is likely to have many individual heat pumps which are difficult to hydraulically link.

7) Identification of the impact of load topology on the overall system efficiency

In 3rd generation district heating networks, the load topology (or demand placement) has been well documented i.e. situate the largest demands close to the primary energy center to reduce the pipe diameter and thermal loss. However, in ambient temperature networks the same principles do not apply. This was demonstrated for the first time through a dynamic optimization model. It was shown that where a large heating or cooling demand is placed adjacent on the hydraulic network, the opposite efficiency was increased i.e. where a large heating demand is placed prior to a cooling demand, the cooling COP of the adjacent building is increased by the rejected coolth to the ambient loop. The decision to include building demands into a network is usually reserved for new masterplan developments. In retrofit, the decision is usually which demands to exclude. This is where this is incredibly important. It has been shown that the demand density has reduced impact on an ambient loop network, therefore greater selectivity is afforded when deciding which demands should be connected. This is in contrast to 3rd generation networks which typically require as large a demand density as possible.

8) Identify the significance of demand density on an ambient loop network.

As mentioned, the demand density has been shown to have reduced impact on the overall effectiveness of the energy network. This is not to say the demand density is insignificant, only that it is of less importance than the demands connected. In 3rd generation networks, the aim is to keep the demand density as high as possible so that the energy being sold per length of pipe is as high as possible, therefore reducing the thermal losses as a percentage of the energy sold. In an ambient loop, the thermal losses are almost negligible.

Although the demand density is less important, the overall length of the network will still have significant impact on the economics of the project. Ambient loop networks operate at much lower temperatures than 3rd generation networks, which means that the primary distribution carrier pipes must be much larger to carry the equivalent amount of thermal energy. This is a compromise that must be made between the overall increase in capital cost of the project and the increased revenue from additional shared energy sales. In the scenarios tested, it was difficult to demonstrate a positive financial case for this.

9) Optimize the design temperature of an ambient loop

In an ambient loop network, both the heating and cooling heat pumps are fed from the same loop. There is therefore a competing interest to increase the supply temperature and favor the heating efficiency or lower the temperature and favor the cooling efficiency. This must be achieved while minimizing the required top-up energy from external sources i.e. the objective is to have the energy network be thermally self-sufficient. It was shown that the supply temperature should be chosen to selectively improve the performance of the largest user on the network, which will therefore give the largest energetic improvement. However, this can also be varied seasonally such that the supply temperature drops in the summer to favor the space cooling efficiency, and increased in winter to favor space heating efficiency. Where large flowrates are used, these become irrelevant as the shared energy will not cause a significant change in the ambient loop temperature such that no improved efficiency is observed from shared energy.

The overall conclusions show the following points to utilize low temperature district energy:

- Priority should first be given to fabric improvements, where economically feasible. This will allow a low distribution temperature within the heat network

- District energy sharing networks should be considered with complimentary load profiles. The greatest benefit of these networks is shown when there is large thermal storage to allow demand side management of rejected heating/cooling

- Larger networks can be considered with connections spread further out as the demand density is of lesser importance in low temperature networks.

7.3. Future Work

As with any project, time and resource constraints prevented various threads of research from being fully explored. The following section details where further work could benefit the research area. Many of these points are political in nature. This reflects the state of technical maturity in the market area, where the policy has not kept up with innovation.

1. Identifying suitable locations for heat network deployment. The limitations of Scottish housing was identified in this thesis, but additional effort should be made to expand this to a wider range of building types. In an ideal scenario, an open source map would be incredibly useful for developers and local authorities to determine where heat networks could be suitable. Both the Scottish and UK governments currently have versions of this in the process, but focus on the types of demand rather than the building topology. This should also focus on the varying types of heat emitters and connection types found in the UK.

2. Investment in building envelope improvements. The UK has a long history, and the buildings we occupy show that. Policy has to reflect the uphill struggle to retrofit low carbon technologies, particularly for private residential buildings. Financial penalties for owners which do not meet increased energy standards run the risk of encouraging fuel poverty. It is therefore very clear that the next step is for significant government investment to support this transition.

3. Clear market control and regulation for thermal energy sharing networks. This is a new and emerging market that needs to learn from previous heat networks. Giving end users routes for recourse will implement trust and support wider adoption. Draft bills have been proposed from the Scottish government, but have been widely criticized as being too “light touch”.

Further market testing and pilot trials for wide scale rollout of reversible heat pumps will be crucial.

4. Open access to operational characteristics of existing heat networks. This information is usually regarded as commercially sensitive, but is important for end users in deciding if a heat network offers a low carbon energy option. A prime example of this is the London City heat network; largely fed from CHP and incredibly high in carbon.

5. Energy tariffs to reflect decentralized renewable energy. Time of use tariffs are uncommon outside Economy 7, which is an incredibly simple method of demand control. Encouraging end users to change energy consumption habits through financial benefits is likely one of the best ways to minimize the impending increase in peak power demand from the electrification of heat.

Appendix 1

Publications

The requirements for an alternative format thesis containing published works is that the text of the publications must be un-altered. As such, changes have only been made to allow the thesis to be understood as a coherent whole (e.g. figure and table numbers, chapter numbering etc.). The work presented in this thesis has been published in peer reviewed journals. Where other authors are listed, this is in a supervisory capacity. My contribution to each section was greater than 50%.

Chapter 2:

Millar M, Burnside N, Yu Z. District Heating Challenges for the UK. Energies. 2019;12(2):310.

Chapter 3:

Millar M, Elrick B, Jones G, Yu Z, Burnside N. Roadblocks to Low Temperature District Heating. Energies. 2020;13(22):5893.

Chapter 4:

Millar M, Burnside N, Yu Z. An Investigation into the Limitations of Low Temperature District Heating on Traditional Tenement Buildings in Scotland. Energies. 2019;12(13):2603.

Chapter 5:

Millar M, Yu Z, Burnside N, Jones G, Elrick B. Identification of key performance indicators and complimentary load profiles for 5th generation district energy networks. Applied Energy. 2021;291:116672.