UNIDIRECTIONAL LOW TEMPERATURE THERMAL NETWORKS:

ENABLING THERMAL DISTRIBUTED ENERGY RESOURCES

UNIDIRECTIONAL LOW TEMPERATURE THERMAL NETWORKS: ENABLING THERMAL DISTRIBUTED ENERGY RESOURCES

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Abstract

This thesis investigates the potential of Unidirectional Low Temperature Thermal Networks (UD-LTTN) as a means to improve community-level energy efficiency through the integration of Thermal Distributed Energy Resources (TDER). UD-LTTN systems are the next generation of District Heating and Cooling (DHC) systems, and utilize decentralized heat pumps to enable distributed generation, reduce thermal pipe losses and decrease system-wide exergy destruction. By providing these benefits, these systems have the potential to decrease the total energy utilization of a community, when compared to traditional DHC systems.

To better understand the potential of UD-LTTN systems, an equation-based modelling library was created in the open-source simulation code "Modelica." This library was then used to perform a comparative analysis between both a UD-LTTN system and DHC system when applied to the same case study. This analysis compared each system based on total energy utilization and carbon emission production for a variety of cases. Additional thematic analysis was then done to understand how the comparative analysis results extend to the more general field of UD-LTTN system design. The results found that UD-LTTNs systems can reduce the total energy generations requirements by capturing energy from decentralized waste energy resources within the community. However, other factors such as electrical generation sources, peak power capacity and pumping power requirements are important considerations when determining the true effectiveness of these innovative systems.

Acknowledgements

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Notations and Abbreviations

Nomenclature

$\dot{m}$	Supply Pipe Mass Flow Rate (kg/s)
Q	Thermal Energy Flow (W)
T	Temperature (C°)
W	Electrical Work (W)

Subscripts

bc	Building Side (cooling demands)
bh	Building Side (heating demands)
c	Cooling (various)
cs	Cold Supply (temperature)
h	Heating (various
hs	Hot Supply (temperature)
r	Return (temperature)
s	Supply (temperature)

Abbreviations

5GDHC	5th Generation District Heating and Cooling
BD-LTTN	Bidirectional Low Temperature Thermal Network
CHP	Combined Heating and Power
COP	Coefficient of Performance
DC	District Cooling
DHC	District Heating and Cooling
DH	District Heating
ETS	Energy Transfer Station
ETSC	Energy Transfer Station (cooling)
ETSH	Energy Transfer Station (heating)
EMC	Energy Management Centre
HDPE	High-Density Polyethylene
HVAC	Heating Ventilation and Air Conditioning
LTTN	Low Temperature Thermal Network
ON	Ontario
PE	Primary Energy
PID	Proportional-Integral-Derivative
UD-LTTN	Unidirectional Low Temperature Thermal Network
TDER	Thermal Distributed Energy Resource

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Chapter 1

1. Introduction of Problem Statement

Residential heating demands account for approximately 5.5 PWh of global energy production per year [1]. Although the majority of this energy is for seasonal thermal conditioning, 45% of this generation is used for domestic hot water demands throughout the year [1]. Meanwhile, air conditioning is on the rise. In 2016 it was estimated that globally commercial and residential air conditioning required 2.02 PWh of electricity [2] and this demand is expected to increase at a rate of up to 7% each year until 2100 [3]. As climate change continues, and the developing world continues to have more efficient access to electricity, this rate of adoption will only quicken [4].

These heating and cooling trends, although opposite in nature, have the potential to be mutually beneficial. In most cases, air-conditioning leads to the rejection of low-quality thermal energy, and this energy has traditionally been deemed unusable because of its rejection temperature (40°C). However, through innovations in refrigeration cycle technology, new integrated community energy systems can capture this low-quality energy and integrate it as a Thermal Distributed Energy Resource (TDER) within the community.

TDER are decentralized sources of thermal energy within a community. These include cooling processes such as air conditioners or industrial chillers as well as process heat that is created by both industrial and commercial processes. In both cases, if communities can integrate these energy resources as part of their thermal generation mix, the whole community can benefit from increased energy utilization.

One system that can integrate these distributed thermal energy resources is a Unidirectional Low Temperature Thermal Network (UD-LTTN). UD-LTTN systems are part of the 5th Generation District Heating and Cooling (5GDHC) systems and feature a variety of innovations that allow them to integrate DTERs and supply both heating and cooling loads simultaneously. UD-LTTN systems differ from traditional District Heating and Cooling systems (DHC) by being specifically designed for TDER integration.

Whereas traditional DHC systems provide for community energy requirements using two, two-pipe parallel piping networks that connect each community building to a centralized generation facility (Figure 1), a UD-LTTN includes an innovative series piping network design. This series piping network consists of a singular pipe that connects to each building in series rather than parallel. Since there is only one pipe, the UD-LTTN design includes two water to water heat pumps between the building connection and the supply pipe (Figure 2). This dual heat pump integration allows the UD-LTTN to simultaneously provide for both the heating and cooling loads within the building. These heat pumps can use the piping network as a source or sink for thermal conditioning and provide for the building's thermal conditioning demands. In this way, when buildings connected to the UD-LTTN require cooling, the low-quality energy removed from the building is rejected into the piping network and can be used by other buildings with heating demands. As such, if these heating and cooling demands occur simultaneously, an energy sharing benefit is realized. By sharing energy, the UD-LTTN system can reduce the amount of waste energy rejected to the environment and increasing the energy utilization of the community.

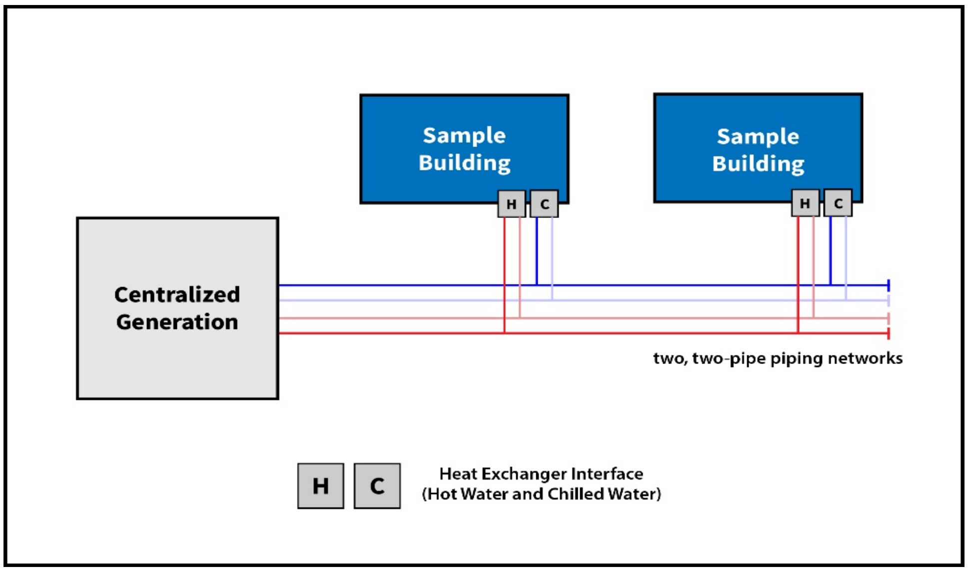

Figure 1 District Heating and Cooling (DHC) System configuration

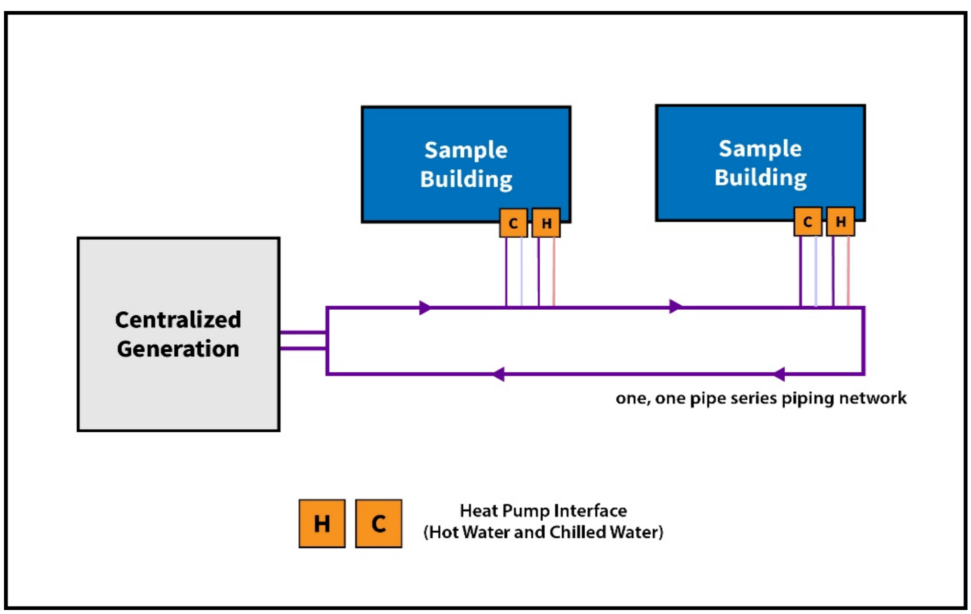

Figure 2 Unidirectional Low Temperature Thermal Network (UD-LTTN) Configuration

To realize this TDER integration, however, electrical work is required to operate the decentralized heat pumps located at each building. This electrical work represents a high-quality energy source being used to subsidize a low-quality thermal conditioning process. As such, research is required to understand the nature of this TDER integration, and whether the energy recovery benefit is worth the additional electrical energy demands.

This thesis builds on previous UD-LTTN research endeavours and investigates the integration of TDERs by performing a comparative analysis between a UD-LTTN and DHC system. The comparative analysis was done using a modelling library developed in Modelica. Modelica is an object-oriented modelling language that allows for the creation of open-source equation-based multi-domain models. Within Modelica, models for both DHC and UD-LTTN systems were created and then used to compare the performance of both systems for the same case community.

After the comparative analysis, additional thematic analysis was completed to explore how the trends specific to the case study apply more generally to the field of UD-LTTN system design. Specifically, this thematic analysis focused on the various thermodynamic mechanisms that impact UD-LTTN system performance, the creation of an analytical solution that can predict the energy sharing potential of communities and the different thermal energy sources that should be considered when designing UD-LTTN systems.

The following chapters provide a summary of the work done. Chapter 2 covers the history of DHC, the innovations that have led to the development of 5GDHC systems and highlights potential gaps within the literature. Chapter 3 describes the modelling methodology used, the Modelica library that was created and the numerical and experimental checks that the library underwent. Chapter 4 describes the parameter selection analysis done ahead of the comparative analysis. Chapter 5 summarizes the comparative analysis performed and compares the UD-LTTN and DHC systems based on total energy utilization, carbon emissions, peak power requirements, thermal pipe losses and pipe pumping power. Chapter 6 highlights the thematic analysis and discusses the various thermodynamic mechanisms that impact UD-LTTN system performance as well as the analytical solution developed to measure energy sharing potential. Finally, Chapter 7 discusses the impact of the integration of TDERs and gives recommendations for future work.

Chapter 2

2. Literature review

2.1 District Energy Systems

Since the 1870s District Heating and Cooling Systems (DHC) have existed as a means to provide thermal conditioning to communities. In general, DHC systems require three main components; affordable thermal sources, community thermal demands and pipes to serve as connections between the sources and demands [5]. This section outlines the history of these systems and their important operational considerations.

2.1.1 District Heating

The 1st Generation of District Heating (DH) started in the 1870s and utilized pressured steam as the primary working fluid [6]. These district heating networks used iron pipe insulated with mineral wool and operated at pressures as high as 80 psi (551.6 kPa). Generally, the centralized plant created steam by burning coal and distributed the thermal energy to both industry and residential clients alike. Although this technology was effective, the heat losses associated with the high supply temperatures and the corresponding dangers of pressurized steam made the system undesirable.

Around the 1920s, the 2nd generation of DH was established using water as the working fluid because of its higher heat capacity. This increased heat capacity led to a transition away from steam to pressurized water often conditioned to over 100˚C. By switching from high-pressure steam, DH systems became easier to manufacture, and this led to higher rates of adoption. Initially, these systems were adopted by Germany in the 1920s and then by the Soviet Union and China in both the 1930s and 1950s, respectively [7].

By the end of the 1970s, the researchers established the 3rd Generation of DH, which further reduced the supply temperatures to below 100°C. This temperature reduction allowed for reduced supply pressures associated with the system and made DH components mass-manufacturable [8]. This 3rd Generation is sometimes referred to as "Scandinavian district heating" as most of the components were mass manufactured in Scandinavia. Since the 1970s, these systems have since become prolific, and as of 2004, there is over 70,000 PJ of annual District Heating annual capacity installed across 80 000 different sites globally [9].

Today, regardless of location, DH systems operate using energy from either fossil fuels, renewable energy resources (solar thermal or geothermal) or recycled heat from industrial processes. When systems rely on fossil fuel generation, they often utilize combine heating and power (CHP) generation. CHPs capture high-grade waste energy from an electrical generation process and use this thermal energy as a thermal source for DH operations. These CHP-DH systems have been found to increase primary energy utilization by up to 40% when compared to traditional electrical power plants [10]. This increased efficiency has led to increased adoption

CHP-DH in some countries such as China and Finland, where CHP-DH accounts for 62.9% and 80% of all DH systems, respectively [11].

Beyond energy efficiency, another important DH consideration is the decarbonization of thermal energy sources. In support of this goal, work is being done to utilize both biofuel CHPs and industrial waste energy sources for DH operations [12]. Specifically, the integration of waste energy sources has become increasingly successful with DH systems around the world utilizing more recycled and renewable heat (56% and 9%) than fossil fuels (35%) [9].

2.1.2 District Cooling

Comparatively, District Cooling (DC) systems are a newer method for delivering thermal energy. These systems were established in the 1960s and are based off pipeline refrigeration systems which were well established in New York City since the 1890s [5]. While pipeline refrigeration systems distributed refrigerant to buildings within a community, DC systems utilize centralized electrical chillers to distribute chilled water. Unlike DH, DC is less established with only 300 PJ of estimated annual capacity present around the world [9].

2.1.3 DHC Demand Patterns

Generally, DHC systems provide energy for thermal conditioning and domestic hot water (DHW) consumption. Thermal conditioning includes both space heating, space cooling and refrigeration. Generally, these demands are seasonal, with peak heating demand occurring in the winter, and peak cooling demand occurring in the summer. However, some buildings, such as data centres and grocery stores, have consistent space cooling and refrigeration demands regardless of the season [13][14]. As such, these buildings types often lead to the DHC systems having baseload cooling requirements.

DHW demands include all the hot water demands within the building. These include typical residential operations such as bathing or cooking, as well as the hot water demands of more intensive commercial and industrial processes. Unlike thermal conditioning demands, DHW demands are consistent throughout the year, with only marginal increases in demand during the winter season [15].

2.1.4 DHC Piping Network Designs

Traditionally DH and DC systems operate using a two-pipe configuration. In these systems, the centralized generation facility connects to each building within the system in parallel through both a supply and return pipe. At each building, a heat exchanger is used to transfer energy from the district pipes to the building's thermal systems. For systems that provide both DH and DC, each process requires its own set of supply and return pipes, and this results in a four-pipe configuration (Figure 3).

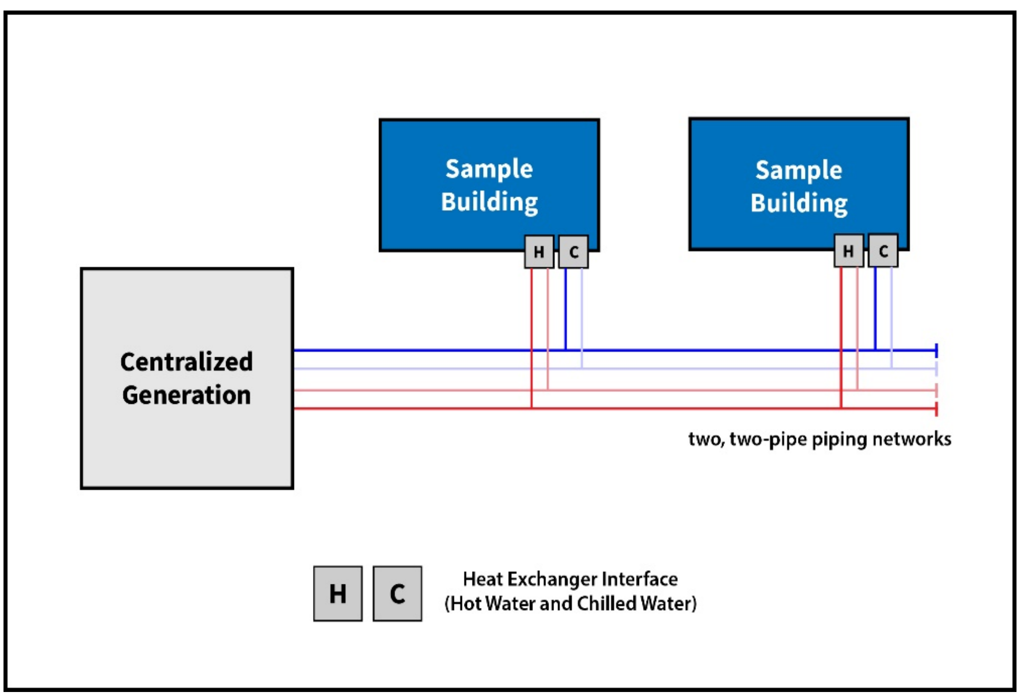

Figure 3: General District Heating and Cooling (DHC) Configuration

Today, modern DH systems utilize steel pipes insulated by polyurethane for their distribution networks. Although these piping design specifications reduce the thermal losses of the system, the installation of such a network can often represent over 75% of a DHC system's capital expenses [16]. With this in mind, there has been an increasing focus on developing flexible plastic pipes that would reduce the associated material costs and provide greater design flexibility [17]. Although these flexible pipes are a promising area of research, utilizing uninsulated plastic piping would increase the thermal pipe loses from the DH system to the environment. This increase is of concern, as the thermal pipe losses from low-density DH systems can account for up to 20% of the DH systems' total energy generation requirements [18]. With this in mind, although flexible piping may reduce the capital costs of a DHC system, it may also lead to increased operational costs due to the higher system-wide thermal losses.

Beyond individual pipe design innovation, other research has focused on the feasibility of multi-pipe insulation methods. It has been shown analytically that twin pipes, which insulate both the supply and return pipes within the same casing (Figure 4), have the potential to reduce pipe losses by up 32% when compared to traditional insulation techniques [19]. Furthermore, experimentally validated finite element analysis models have found that double pipes (Figure 4), which build on twin pipes and include changing supply pipe diameters, were found to further decrease pipe losses by up to 12% [20].

In contrast, due to the low temperatures associated with DC, these systems tend to use uninsulated high-density polyethylene (HDPE) pipes. These pipes are generally larger in diameter, due to the smaller change in temperature between the system's supply and return pipes [21].

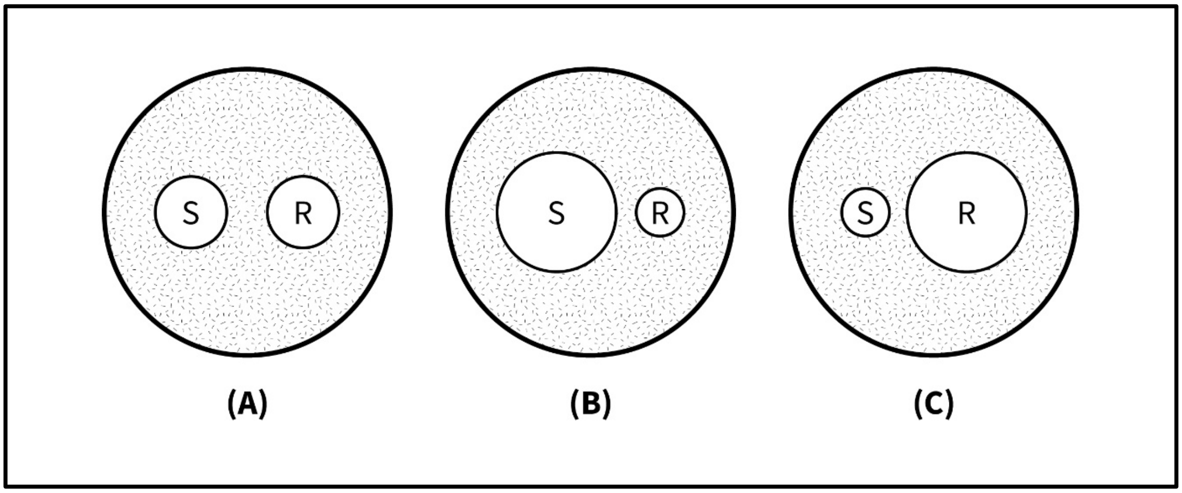

Figure 4 Examples of District Heating Pipe Specifications

(A) An example of a twin pipe with identical supply and return diameters surrounded by the same insulation casing. (B) An example of a double pipe supply specification with a larger diameter favouring the supply pipe. (C) An example of a double pipe return specification with a larger diameter favouring the return pipe.

In general, district pipes specifications (diameter, roughness and material) are determined by the peak energy demands of the DHC system. Since the DHC system's mass flow rates increase proportionally with the community's demands (Section 2.1.6), pipe specifications are chosen according to the community's peak mass flow rates (peak demands), in order to reduce the pressure losses and pumping power requirements of the system. In general, through appropriate district pipe specifications, the hydraulic pumping power requirements of densely populated DHC systems are negligible compared to the thermal energy demands of the community. However, for low-density DHC systems, which have larger distances between the energy sources and consumers, some systems can have pumping power requirements as high as 2.0 kWh/m^2 per year (where per m^2 refers to the area of the DHC system) [22]. These large losses have led to some researchers focusing on developing distributed pumping systems which can potentially improve hydraulic performance through more advanced control systems [23].

2.1.5 Integration of Thermal Distributed Energy Resources

Distributed energy generation has been proven to be a more reliable and environmentally responsible practice than traditional centralized generation techniques [24]. As communities shift to more decentralized electrical generation techniques, it is important that DHC systems also shift to integrate decentralized thermal energy resources. These thermal sources could include solar thermal systems, decentralized cooling machines or decentralized waste energy sources from commercial or industrial processes.

To better understand this integration, work has been done to optimize DH parameters to more efficiently integrate these decentralized energy sources. For some specific cases, this resulted in lowering the supply temperature of the system to 70˚C in the winter in order to maximize the capture of low-grade waste heat [25]. Similarly, in other studies, it was found that although heat pumps can be used to integrate low-grade energy and reduce primary energy consumption by over 10%, additional reductions would be possible by lowering the supply temperature of the network and eliminating the need for heat pumps when capturing waste energy [26].

With regards to industrial waste energy sources, the barriers to energy capture are often policy related rather than technology-based. Specifically, in Sweden, it was found that although the country uses 2.75 TWh/year [27] of waste energy for DH operations, there is a predicted additional 2.0 TWh/year of primary energy available for direct capture by DH systems [28]. Additional to primary energy sources, the same study also predicted 19 TWh/year of low-quality waste energy sources available for capture. Although these energy sources are low quality, heat pumps could be used to increase the rejection temperature, thus making them a feasible alternative to centralized generation. While these energy sources are technically accessible, these projects are often only possible when the industry partner has a strategic mandate to sustainable energy systems and deems the project worth the financial risk [29].

2.1.6 District Energy System Operational Parameters

For each piping network in a DHC system, three general parameters characterize the system's total energy output. These are the systems mass flow rate ($\dot{m}_s$), supply temperature (T_s) and return temperature (T_r) (Figure 5). Generally, $\dot{m}_s$ is proportional to the total demand within the system [30]. This proportionality is because both the thermal generation equipment and the heat exchangers within the buildings have preferred supply (T_s) and return (T_r) temperatures [31]. As such, in traditional control strategies, the mass flow rate of the system fluctuates with the community's demands so that these temperature differences ($T_s - T_r$) can be maintained.

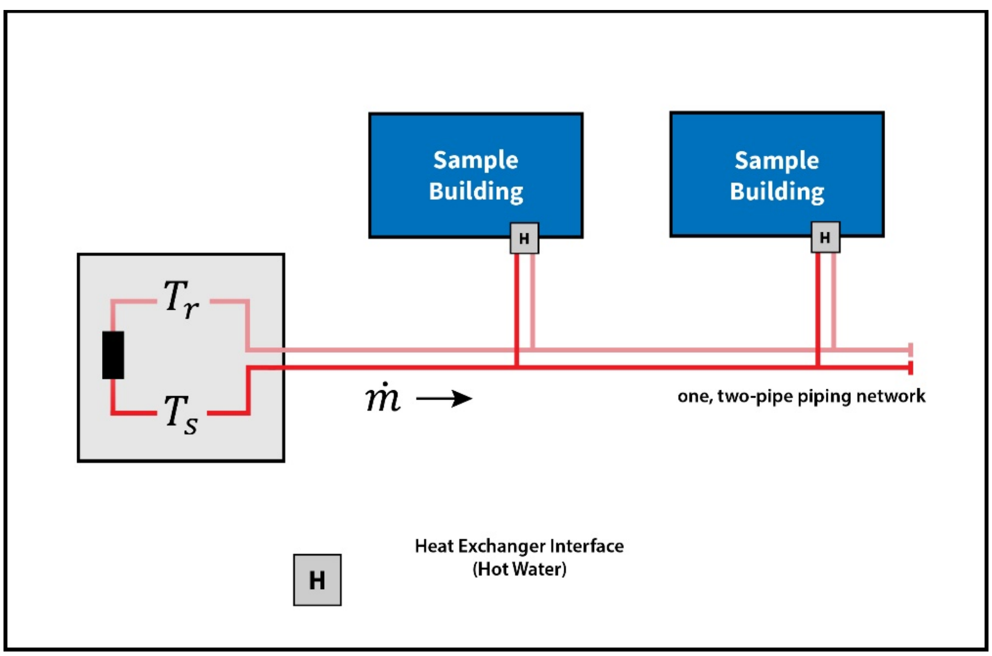

Figure 5 Labeled District Heating and Cooling (DHC) System

Beyond system control, for DH and DC, additional considerations must also be given to the network supply temperatures (T_{hs} for district heating and T_{cs} for district cooling). These supply temperatures are the temperatures maintained by the central generation facility in order to meet the demands of the buildings within the network. For District Heating, T_{hs} must be set to meet both the thermal conditioning and domestic hot water demands of the community and as such ranges from 70˚C to 110˚C. For District Cooling, T_{cs} ranges from 5˚C to 10˚C depending on the building Heating Ventilation and Air Conditioning (HVAC) system requirements.

Specifically, for DH, the system's supply temperature is especially of concern as lower supply temperatures can reduce the thermal pipe loses associated with the system. With this in mind, work has been done to fluctuate this temperature based on differing demand patterns to reduce thermal pipe losses and optimize generation scheduling [32]. In these studies, the optimal supply temperature was found to range from 90˚C to 115˚C depending on the season.

Work has also focused on fluctuating T_{hs} to optimize the production planning of decentralized production units for thermal energy generation [33][34]. By changing T_{hs}, different thermal production units can be used more efficiently, and this can improve the overall energy utilization of the system. Although these case studies generally resulting in lowering T_{hs}, the equipment constraints ($T_s - T_r$) often prohibit the true optimum from being reached. This result is indicative that to further lower T_{hs}, DH systems will have to be redesigned to accommodate lower temperatures.

2.2 Low Temperature Thermal Networks (LTTN)

Low Temperature Thermal Networks can be considered the next generation of district heating (Generation 4 and 5). These systems further reduce the supply temperatures within the system by integrating heat pumps (Generation 4) and then use this lower supply temperature as a means to provide both heating and cooling from the same piping network (Generation 5).

2.2.1 Integration of Heat Pumps

DHC systems integrated heat pumps to further lower T_{hs} and recover more energy from low-quality waste energy sources. Although previous DHC systems featured heat pumps, improvements in heat pump performance over the last two decades have made the technology a more economical means for thermal energy recovery [35]. In turn, this has led to increased integration of heat pumps at all levels of DHC systems, advancing the field of work and creating a new branch of study called Low Temperature Thermal Networks (LTTN).

The first research on LTTN focused on exergy analysis. Since heat pumps utilize high-quality electrical energy to provide heating, it was important to assess whether these exergy losses are worthwhile. Whereas exergy analysis of traditional DH systems often indicate that lowering T_{hs} can reduce exergy destruction [36], exergy analysis of LTTNs with heat pumps is less conclusive. Since lower T_{hs} can lead to decreased heat pump performance which in turn increases exergy destruction, exergy analysis of LTTN instead focuses on the characterization of exergy efficient communities. This analysis showed that for LTTNs, building density and demand diversity are both important factors when considering exergy destruction [37]. In general, this analysis found that increased building density reduces the pumping power required by the system, while load diversity reduces the central generation requirements by making use of decentralized cooling.

Beyond heat pump specific exergy analysis, research has also found that LTTNs can reduce the system-wide exergy destruction by supplying low-quality energy (low T_{hs}) to buildings which have low quality heat demands [38]. In these Passive House [39] type communities, the HVAC systems operate with supply temperatures as low as 35°C, and this decreases thermal pipe losses and in turn decreases the total exergy destruction. However, if these buildings have domestic hot water (DHW) demands, a secondary piece of generation equipment is required to condition the domestic hot water supply (heat pump or electric boiler). These hybrid DHW LTTN systems have been extensively reviewed in the literature [40][41][42][43] and are a promising design as building envelope efficiency continues to increase (Figure 6).

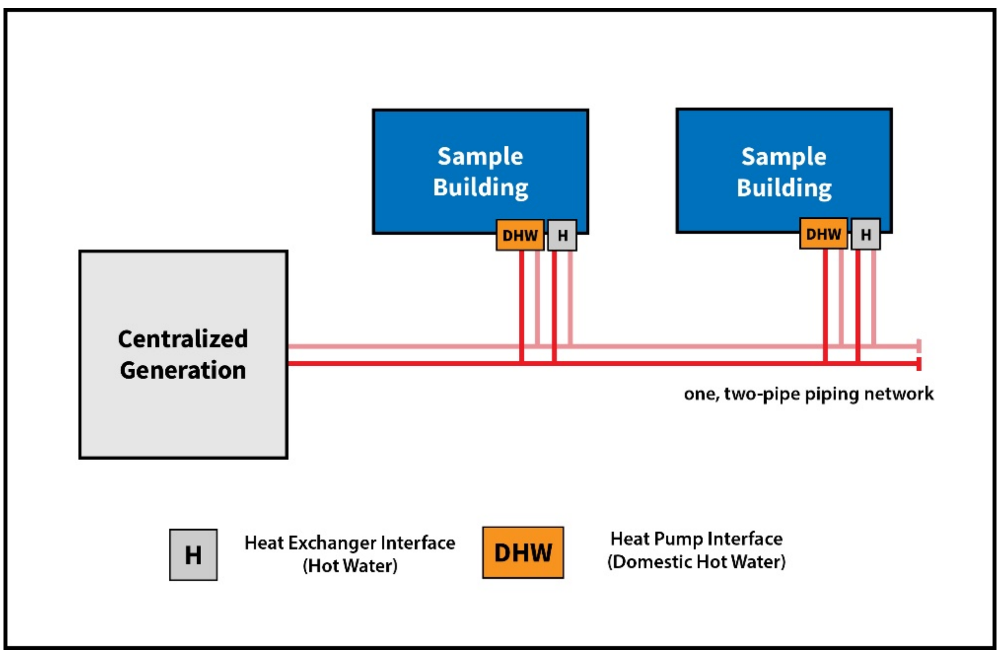

Figure 6 Hybrid Domestic Hot Water Low Temperature Thermal Network System

This system provides for all the domestic hot water (DHW) and thermal conditioning demands of the community. In this system, the DH network supplies low temperature hot water to the high efficiency building for space heating using a heat exchanger. For the DHW demands, the DH network is used as a source for a water to water heat pump which increases the supply temperature to the DHW setpoint.

Other research has focused on novel ways to eliminate the need for decentralized domestic hot water generation. In one case study, the decentralized heat pumps are replaced by a centralized heat pump that cycles the thermal network's supply temperature to the DHW supply temperature periodically throughout the day [44]. During this high-temperature period (70°C), the thermal network is used to charge decentralized DHW storage tanks that are then used to meet the community's DHW demands throughout the day. This case study found that Non-Uniform Temperature District Heating is more effective than both the hybrid DHW LTTN systems and low-temperature DH systems. However, additional research must be done to understand the operational limitations of using decentralized storage tanks that rely on periodic charging.

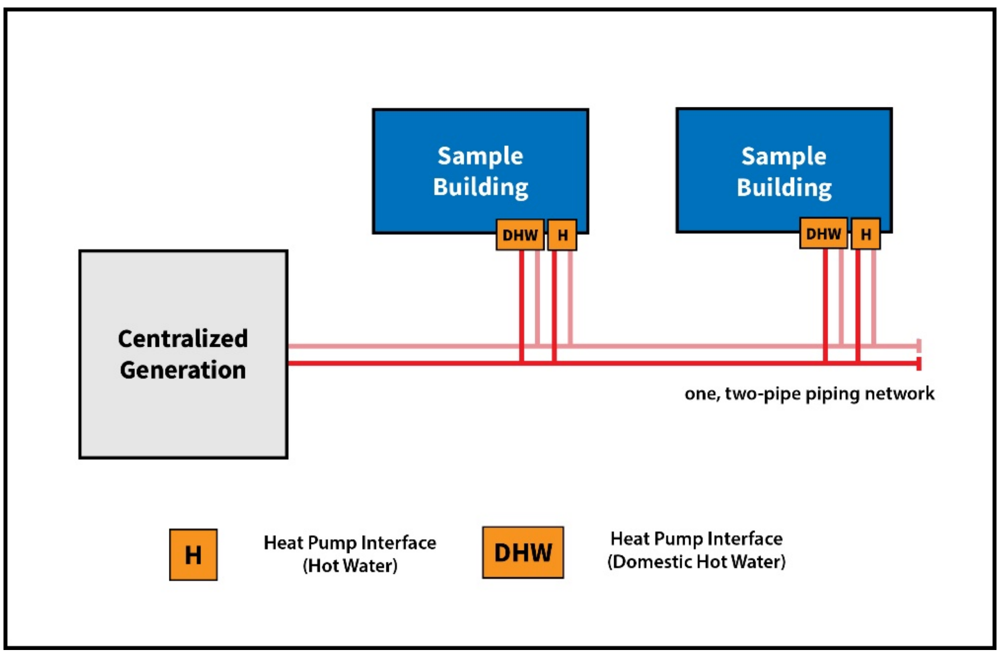

Figure 7 Retrofit Low Temperature Thermal Network System

In cases where buildings have high-temperature heating demands, retrofitting existing DH systems to meet LTTN specifications is also possible. These systems include a decentralized heat pump at each building that interfaces with a LTTN that has a supply temperature ranging from 10°C – 30°C. For retrofit applications due to the high-temperature heating demands, these heat pumps supply both the building's DHW demands and thermal conditioning demands (Figure 7). In some cases, these systems require two heat pumps when the HVAC temperature requirements are much higher than DHW needs (80°C – 100°C). However, these high-temperature HVAC systems generally have poor heat pump performance, which in turn leads to higher exergy destruction and inefficient primary energy utilization. These retrofit implementations are less researched within the literature and represent an interesting opportunity within the field.

2.2.2 Integration of District Cooling

Whereas traditional DHC systems required communities to interface with two separate district piping networks for DH and DC, LTTN systems with heat pump integration can provide both heating and cooling using a singular piping network (Figure 8). This duality is made possible by having two heat pumps at each building, each interfacing with the same supply pipe, one providing heating and the other providing cooling. In addition to dual heat pump integration, the supply temperature of these systems must also be lowered to around 10˚C to 20˚C in order to accommodate the design constraints of the heat pumps [45]. It was this integration of cooling demands that established the 5th Generation of District Heating and Cooling (5GDHC). With this new generation comes novel piping designs (Section 2.2.3) and the potential for increased integration of Thermal Distributed Energy Resources (TDER) (Section 2.2.4).

2.2.3 5GDHC Piping Network Designs

Although LTTNs can integrate heat pumps with a traditional two-pipe piping network, to provide for both heating and cooling demands, some design revisions were required. At a high level, these new designs include two different categories, unidirectional thermal networks and bidirectional thermal networks. These systems, have become increasingly prominent within the literature, with multiple research groups working towards characterizing these complex systems [46][47].

In a Unidirectional LTTN (UD-LTTN), the design consists of a single supply pipe that connects to each building within the community in series. At each building, both heating and cooling heat pumps interface with this supply pipe to provide thermal conditioning to the building [47] (Figure 8). In this series framework, the LTTN supply connects to both the supply and return connections of the building heat pump and thus mixing occurs within the LTTN supply pipe at each building. To provide for both these thermal operations, the temperature in this supply pipe is moderate and ranges from 10˚C to 20˚C. This single pipe design is especially common in locations where there is an extensive source of ambient energy (ground or surface water) that can be used to condition the thermal network [48].

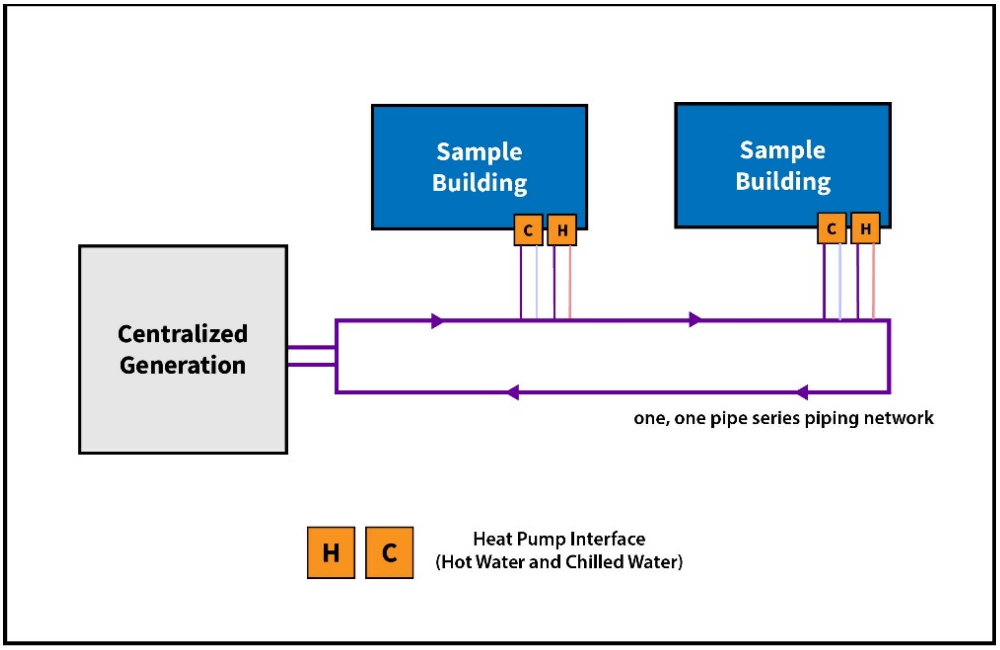

Figure 8 Unidirectional Low Temperature Thermal Network (UD-LTTN) System

In the UD-LTTN system a single supply pipe connects to each building in series. At each building, heat pumps use the supply pipe as a source to create hot and chilled water for thermal conditioning.

The Bidirectional LTTN (BD-LTTN) system builds on this unidirectional system by adding a second supply pipe. These two pipes supply two different supply temperatures, with the cold pipe ranging from 10˚C to 15˚C and the warm pipe ranging from 15˚C to 20˚C. Now instead of providing for both heating and cooling operations from the same supply, each operation would have a preferred supply temperature (Figure 9). For cooling operations, the heat pump would draw from the cold supply pipe and would return the working fluid to the warm supply pipe. In this way, the system can achieve a higher coefficient of performance (COP) for the cooling operation and can also provide decentralized thermal generation for the warm supply pipe. For heating operations, the opposite would occur with the heat pump drawing from the warm supply line and returning water to the cold pipe. In this way, the bidirectional system has the potential to be more efficient than the unidirectional system by increasing the COPs of both thermal processes and reducing the electrical requirements of the system [46].

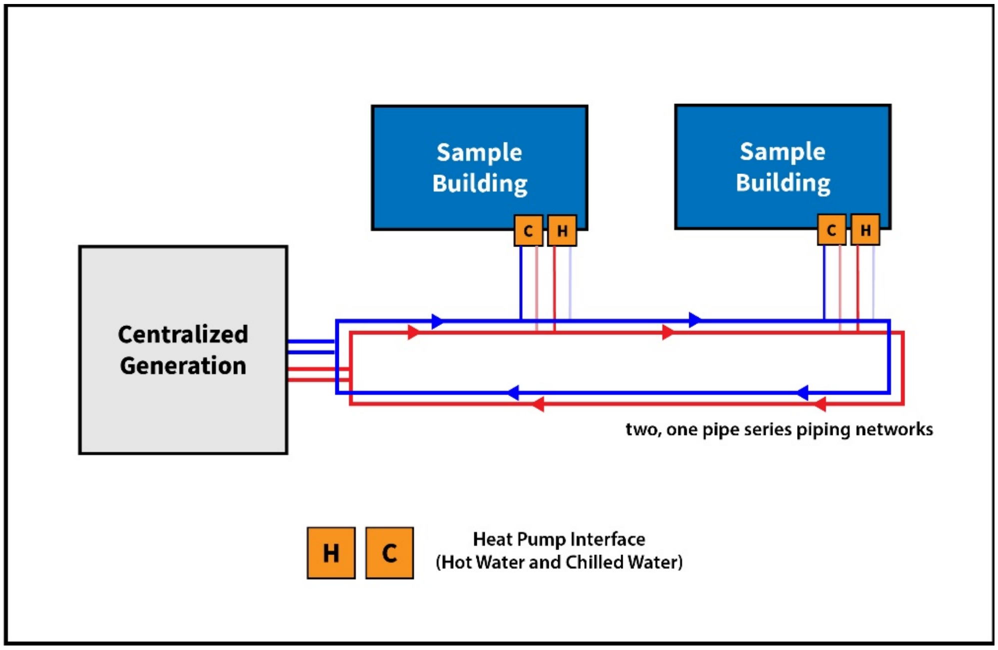

Figure 9 Bidirectional Low Temperature Thermal Network System

In the BD-LTTN system both a warm and a cold supply pipes connect to each building in series. At each building, heat pumps use the supply pipes as a source to create hot and chilled water for thermal conditioning.

This increased efficiency has led to the wider adoption of the bidirectional system with numerous BD-LTTN systems installed across the European Union as of 2019 [46]. However, some of these systems have reported large pressure drops across the bidirectional building interface [49], and other systems have reported higher electrical utilization than originally anticipated (85% higher pumping requirements, 53% higher heat pump demands) [50]. These irregularities an indictive that more research is required to better understand the operational parameters and design requirements of these systems.

2.2.4 5GDHC Integration of Thermal Distributed Energy Resources

This ability to provide for both heating and cooling from the same network is a unique benefit of decentralized heat pump integration and allows for more efficient sharing of thermal energy between buildings. Whereas with traditional DHC systems all cooling and heating process occurred independently of each other, by combining the heating and cooling operations into a singular process the UD-LTTNs and BD-LTTNs can take advantage of cooling operations to subsidize heating generation requirements. Unlike traditional DHC systems, this benefit is possible without the need for large booster heat pumps [26] (2.1.4). To better understand this opportunity, consider the case community shown in Figure 10 and Figure 11. This example consists of a simple two-building community where one building is cooling dominant, and the other building is heating dominant. This simultaneous demand could occur during the Fall or Spring seasons when space conditioning demands are mixed, or it could be the result of two dissimilar energy consumers such as grocery store (predominantly cooling) and a swimming pool (predominantly heating).

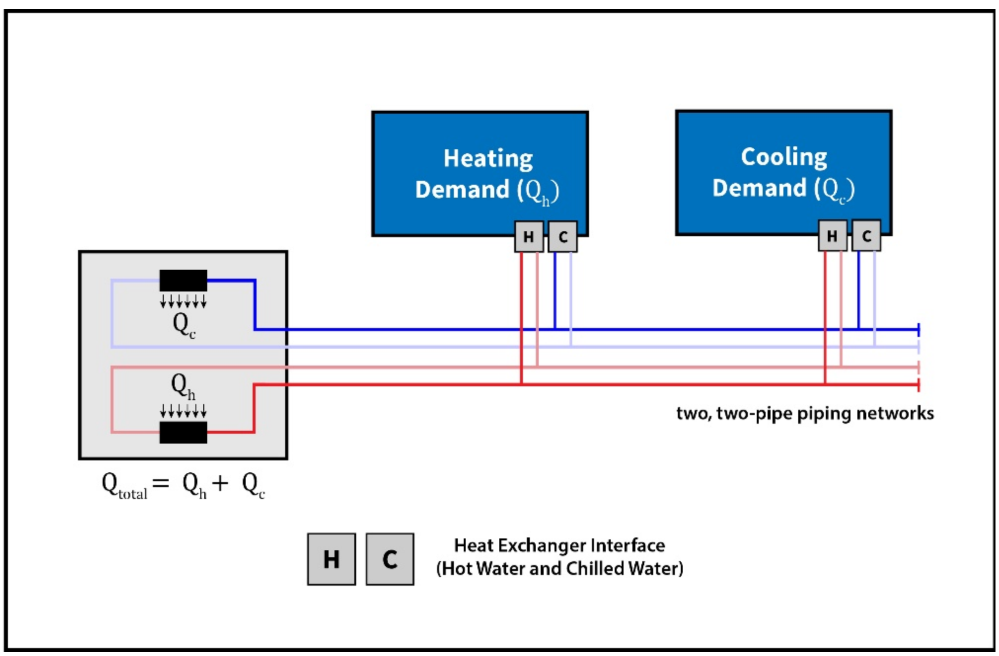

Figure 10 District Heating and Cooling (DHC) Energy Sharing

Using a traditional DHC system (Figure 10), both buildings are supplied by separate piping networks and pass their energy demands to two centralized plants which provide the necessary thermal conditiong.

However, with a UD-LTTN (Figure 11), since both thermal conditioning processes are supplied by a heat pump that interfaces with a singular supply pipe, their corresponding loads are passed on to a singular centralized plant. Instead of providing for both heating and cooling independently, this centralized plant must instead condition the difference between the two simultaneous demands. This change is because while the heating process rejects cold water into the return pipe, the cooling process rejects warm water. These two returns then mix within the LTTN supply pipe, thus allowing the excess heat from the cooling process to be used as an energy source for the heating process.

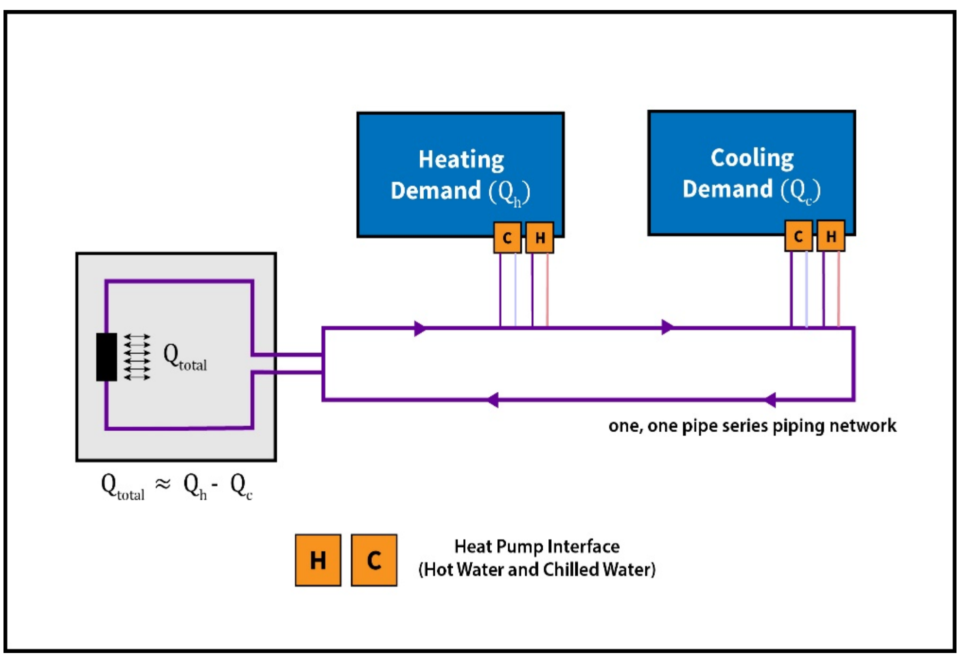

Figure 11 Unidirectional Low Temperature Thermal Network (UD-LTTN) System Energy Sharing

For the BD-LTTN, a similar process occurs. Since the heating process rejects cold temperature water to the cold pipe, and the cooling process rejects warm water to the warm pipe, each thermal operation can reduce the centralized generation requirements of the other supply pipe. In this way, the buildings can share energy, even without the mixing of supply and return streams.

This sharing process has the potential to reduce the total energy utilization of the system by reducing the energy wasted to the environment by the cooling process. However, this benefit is the result of the heat pump integration, and as such, it is important to consider the additional electrical work that comes with integration and its potential effects on total energy utilization.

Beyond sharing energy between community members, by lowering the pipe temperature to 10°C to 20°C, a UD-LTTN can more efficiently capture waste energy from decentralized energy sources without the need for booster heat pumps. Since most low-quality waste energy sources have rejections temperatures of around 40°C to 50°C, UD-LTTN systems make it possible to capture this waste energy using a simple heat exchanger connection [51]. This further increases the potential for integration of decentralized thermal energy resources.

2.2.5 5th Generation Operational Parameters

When compared to traditional DHC systems, 5GDHC systems require additional design analysis in order to determine the optimal operational parameters. This additional analysis is because series piping networks have different designs constraints than traditional two-pipe systems.

For the BD-LTTN, each supply pipe has a supply temperature, T_{s1} and T_{s2} (Figure 12). These two pipes supply two heat pumps within the buildings, and these heat pumps provide either heating or cooling at building's preferred supply temperatures (T_{hs} for heating, T_{cs} for cooling). Additionally, each supply pipe within the thermal network has its own corresponding mass flow rate, $\dot{m}_1$ and $\dot{m}_2$.

For the UD-LTTN, the singular supply pipe has a supply temperature T_s, and a mass flow rate $\dot{m}$ (Figure 13). Like the BD-LTTN, this supply pipe interfaces with two heat pumps at every building, which then provide heating or cooling at the buildings preferred supply temperatures (T_{hs} for heating, T_{cs} for cooling).

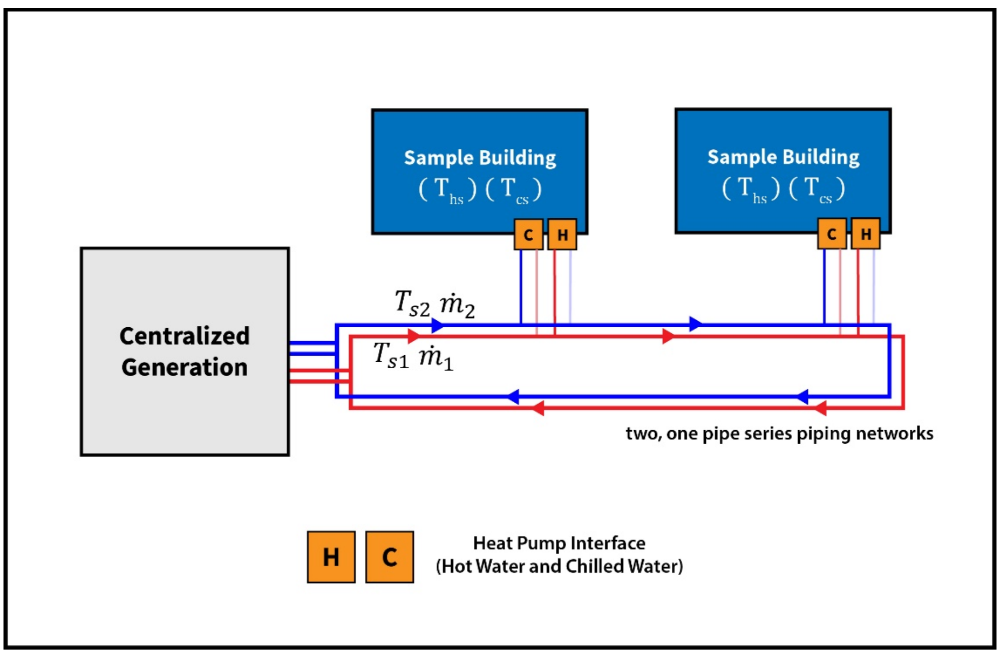

Figure 12 Labeled BD-LTTN System

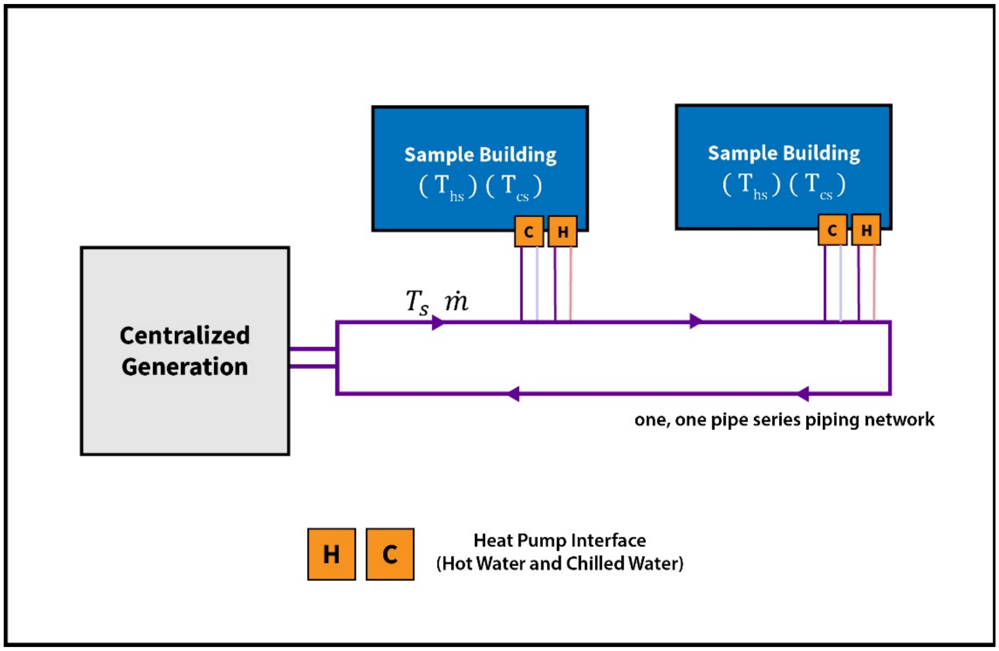

Figure 13 Labeled UD-LTTN System

In contrast to traditional DHC systems, the supply temperatures (T_s, T_{s1} and T_{s2}) in both the UD-LTTN and BD-LTTN change dynamically throughout the community due to the series nature of the piping network. This dynamic nature is a unique challenge for supply temperature controls, and some work has been on minimizing fluctuations by using multi-agent controllers [52]. The results found that specifically for BD-LTTN, an agent-based controller that maintains T_{s1} and T_{s2} at their optimal set points can save on average 8.7% on total energy consumption when compared to a BD-LTTN with free-floating supply temperatures.

Although some initial analysis has shown that the optimal supply temperature for both UD-LTTN and BD-LTTN systems could be a constant [52], more research is required to understand how changes in T_s effect communities with high load diversity. Load diversity is an especially important consideration for UD-LTTN systems, where the optimal value of T_s is one that benefits both the heating and cooling processes simultaneously.

The mass flow rates of series systems ($\dot{m}$ for UD-LTTN, $\dot{m}_1$ and $\dot{m}_2$ for BD-LTTN) also requires different considerations than traditional parallel DHC systems. Whereas traditional DHC systems control $\dot{m}$ based on system-wide energy demands, for series systems $\dot{m}$ is a function of system stability. After each building, the temperature of the supply pipe changes based on the demands of the building and the mass flow rate of the supply pipe. If $\dot{m}$ is too small, large changes in building demands will cause large fluctuations in T_s, and this could affect the heat pump performance of other buildings connected to the thermal network. In general, this leads to UD-LLTN and BD-LTTN having high mass flow rates that ensure temperatures stability [50]. However, more work is required to understand how to best determine $\dot{m}$, especially for UD-LTTNs where mixing occurs within the supply pipe.

2.3 Modelling Techniques

Within the framework of District Heating and Cooling systems, there exist two branches of modelling tools, general-purpose and special-purpose tools. General-purpose tools allow for the modelling of district energy systems from a multi-domain perspective, while special-purpose tools focus on modelling a specific domain [53]. For the case of LTTNs, where both electrical and thermal domains are relevant, general-purpose tools are more prevalent. This section will focus on the various general-purpose tools available and their usage within the literature.

TRNSYS has long been the standard tool of choice for thermal fluid analysis since it supports both detailed thermal and electrical modelling. Specifically, TRNSYS has libraries that support the modelling DHC systems, thermal storage and seasonal storage, meaning it has the flexibility to support detailed DHC system design modelling. These capabilities make TRNSYS especially applicable to DH systems that incorporate thermal storage since TRNSYS can perform the detailed thermodynamic analysis without additional software integration [54]. TRNSYS can also be used for exergy analysis of DHC systems [55] as well as the modelling of CHP and thermally driven chiller integration into DHC systems [56]. This detailed modelling approach has proved valuable when analyzing certain aspects of DHC; however, it also makes TRNSYS computationally expensive and reduces its ability to model large DHC networks with multiple building nodes.

For larger networks, researchers often use Modelica. Modelica is an object-orientated modelling language that supports the modelling of complex engineering systems using differential, algebraic and discrete equations [57]. Since Modelica is equation-based, it is not as effective for detailed domain-specific analysis of complex thermal and electrical systems. However, it can be interfaced with other building energy modelling software, such as EnergyPlus, for detailed simulation of large community energy systems [58].

Beyond its ability to interface with other tools, one of the unique benefits of Modelica is its extensive repository of free to use open source libraries. These include packages such as the Buildings Library from the LBNL [59], and the IDEAs library from KU Leuven [60] both which support building energy modelling and DHC assessment. Additional to open source work, research has also been done using Modelica to optimize the performance of DHC by using the Python and the Optimica Compiler Toolkit [61].

Beyond Modelica and TRNSYS, other modelling tools are also used based on simulation requirements. These include CitySim, EnergyPlus, IDA ICE, Neplan, NetSim and Termis [62]. Although some of these platforms are expanding to include DHC models, due to their domain or system-specific nature, these tools are less common within the DHC simulation space.

2.4 Summary

As outlined in 2.2, past research has focused on a variety of different LTTN systems. To date, most of this research has focused on 4th Generation district heating systems which integrate heat pumps into traditional two-pipe DH networks (2.21). These heat pumps allow the system to reduce the supply temperature throughout the network and thus reduce both the thermal losses and exergy destruction of the system.

Although some work has focused on 5GDHC systems, most of this has been on bidirectional systems with an increased focus on exergy analysis and control optimization. This research has yet to address how best to operate these systems, as well as whether these systems work in retrofit applications. Additionally, there is also a gap within the literature regarding the integration of decentralized thermal energy resources with 5GDHC systems.

Decentralized energy resources have proven to be a more reliable framework for energy management, and within 5GHC Generation framework, these resources include distributed cooling and industrial waste energy sources. Although both unidirectional and bidirectional 5GDHC systems can integrate these thermal distributed energy resources, UD-LTTN systems have unique parametrization challenges due to the mixing of supply and return streams at building nodes.

Hence there exists a need to investigate the ability to capture thermal energy from distributed thermal energy resources using UD-LTTNs. This work hopes to accomplish this by analyzing the potential benefits of a UD-LTTN when compared to a traditional DHC system.

Chapter 3

3. Modelling Methodology

In support of this research, a library of Modelica models was created that utilized historical building data to compare the performance of both DHC and UD-LTTN systems for a retrofit application. Before each simulation, a parameter analysis was done to understand the operational parameters of each design within the framework of the case study. From this analysis, each system's ideal operational parameters ($\dot{m}_s, T_s$) were selected and then used throughout the rest of the comparative analysis.

3.1 Historical Building Data

Although building energy models are possible in Modelica, this study uses historical building data to provide the building loads instead of building energy modelling. This substitution allowed the research to focus on DHC modelling without having to consider the complexities and assumptions that come with building energy modelling. In all cases, the historical building load data was recorded at either five- or fifteen-minute intervals for both the heating and cooling demands of each building (measured in watts). The historical building data interfaces with Modelica through a thermal fluid boundary condition. This boundary condition simulates both the supply and return of the building's HVAC system based on the building's current demands.

3.2 Modelica Modeling Library

Modelica is an object-orientated equation-based modelling platform for complex engineering analysis. It facilitates the creation of models that have flexible dependencies. It was specifically chosen for its object-orientated nature and versatility, which will make modelling a variety of different DHC systems and LTTN more feasible. It also benefits from an extensive library of fluid mediums and property tables that are included with the modelling software. Additionally, there is an extensive repository of open-source modelling libraries that make it ideal for the experimentation and evaluation of thermal fluid systems.

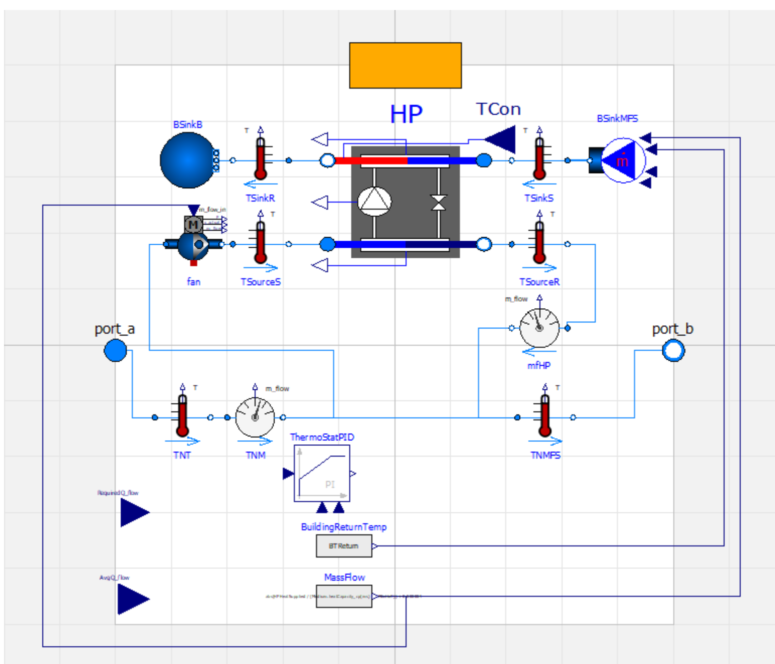

Figure 14 Example Modelica Component Model (ETSH Model)

In this example, the "HP" model has been taken from the open-source AixLib library and has been incorporated into the ETSH componenent model.

For the development of this library, both the Modelica Standard Library and the open-source library AixLib [63] were used. Although both of these libraries have been validated externally by other researchers, additional application-specific verification was also done as a part of this investigation [64][65]. These models were used as sub-models in order to create the UD-LTTN and DHC component models. An example of this sub-model integration is shown in Figure 14.

A total of 31 component models were made to compare the performance of UD-LTTN and DHC systems, and each complex model underwent a series of analytical unit tests. These component models include Energy Transfer Stations, Energy Management Centres, District Pipe models, Building Data Sources and a series of control component models that regulate the simulated system. Section 3.3 and 3.4 include detailed summaries of both the DHC and UD-LTTN models, while Section 3.5 and 3.6 outline both the analytical and experimental assessment processes. Additionally, an example model is included in Section 3.7 and a full summary of the unit tests performed is present in Appendix A.

3.3 DHC Models

Within the Modelica library, the DHC Models form the core of the library. In total, 21 DHC models were created, with three of these further used as base models for the UD-LTTN modelling library. Figure 15 outlines an example of the DHC modelling library being used to model a simple one building community. Within the modelling library, the Energy Management Centre (EMC) simulates the DHC system's centralized generation plant. The District Pipe models represent the system's piping network, and the Energy Transfer Station (ETS) represents the connection between the building and the DHC system (the heat-exchanger). Additionally, the Historical Building Data model provides the ETS model with the building load data, and the Branch Cap model helps to regulate the flow within the district piping network. Throughout the simulation, the

ETS and EMC models communicate using a control port connection to determine the generation requirements within the system.

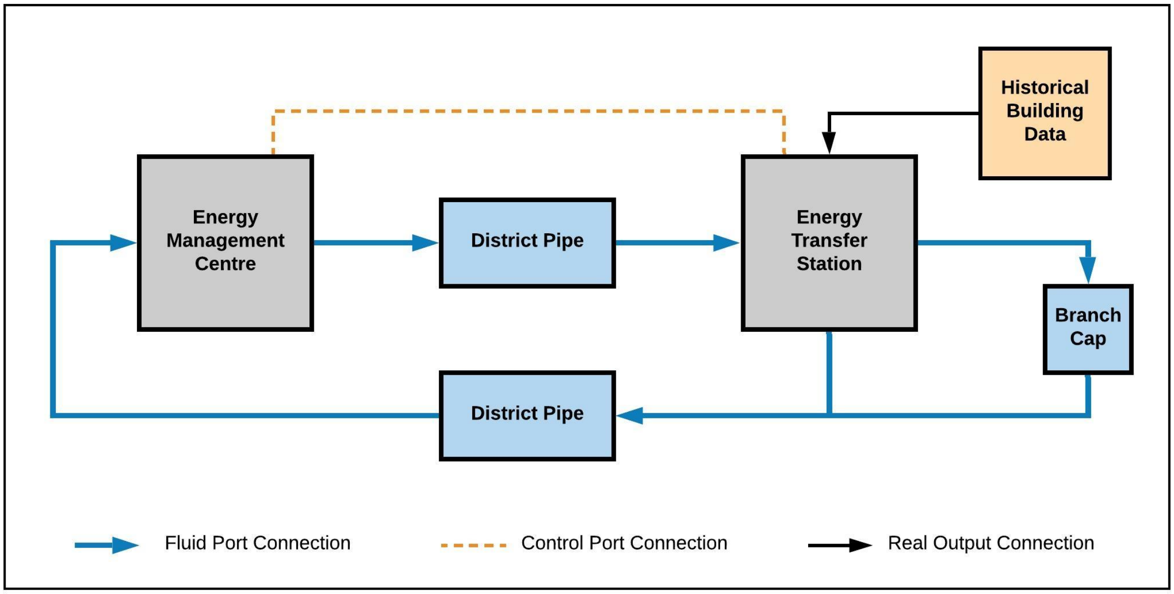

Figure 15 DHC Modelica Library Layout

3.3.1 Energy Management Centre

The Energy Management Centre (EMC) models the central generation facility for the community. Within the DHC framework, this facility provides all of the thermal generation (either heating or cooling) for the entirety of the community. To accomplish this, the EMC connects to the return pipe of the district piping network and calculates the temperature of the return water. It then uses a piece of thermal generation equipment to increase or decrease the temperature of this return water to meet the supply temperature setpoint.

The user sets this supply temperature as per the preferred temperature requirements of the community buildings. Since most pieces of thermal generation equipment have preferred supply and return temperatures, the EMC maintains a constant temperature difference across the generation equipment and instead changes the mass flow rate of the system to meet the community's varying energy requirements. This mass flow rate is controlled by a control block which interfaces with the Energy Transfer Station models (4.1.2) within the community to determine the total community energy demand. From this total, the control block then calculates the instantaneous mass flow setpoint based on the thermal generation equipment's preferred temperature difference and relays this mass flow set point to a proportional-integral-derivative (PID) controller controlling the EMC pump.

For more flexible generation scheduling, the model has replaceable thermal generation equipment for different time of use periods. These replaceable models can be easily substituted for other component models by the user without changing the EMC model's structure. Specifically, the model can change its generation type based on whether it is currently an "on-peak" or an "off-peak" period where "on-peak" refers to the time of day when there is peak electrical consumption (typically 7:00 – 19:00), and "off-peak" refers to time of day when there is less electrical demand (typically 19:00 – 7:00^{+1}). This integration of replaceable periodic generation was implemented to give the user more flexibility when modelling DHC systems.

In total, there are four of these replaceable pieces of generation equipment within the EMC: on-peak heating, off-peak heating, on-peak cooling and off-peak cooling. Whereas the building HVAC systems and in turn, the historical building data form one boundary condition of this investigation, the thermal generation equipment within the EMC represents another. A large body of work is dedicated to the thermal conditioning of DHC systems, and this area of study includes many different equipment types such as combine heating and power plants, boilers, geothermal energy, solar thermal and various refrigeration cycle-based technologies. Since the focus of this work is on the study of DHC designs, the EMC incorporates equation-based analytical models for the thermal generation equipment. In total, this includes four models; an air source heat pump, a ground source heat pump, a CHP and a natural gas boiler. These models calculate the electrical requirements, natural gas consumption, and carbon emission data for the system using fixed COPs and constant energy values. In the future, these analytical models could be replaced with a more intricate physics-based model as the model includes the appropriate supply and return interfaces.

To properly integrate this replaceable framework, the model has six additional parameters that the user must specify. These include one parameter for each of the pieces of thermal generation equipment and two others for specifying the peak period duration.

3.3.2 Energy Transfer Station

The Energy Transfer Station (ETS) model represents the hydraulic interface between the thermal network and the building. Within the DHC framework, this interface consists of a heat exchanger that connects the DHC supply pipe to the building's HVAC system. The heat exchanger itself is taken from the open-source Modelica library, AixLib [63], and allows the user to set a constant efficiency for the heat transfer process. This heat exchanger model can also calculate the pressure losses associated with the ETS heat exchanger. However, since DHC system control is often governed by the maximum pressure losses associated with the piping network, rather than the pressure losses of individual ETSs; this functionality can also be disabled in order to reduce the computation intensity of the model [66].

Beyond the heat transfer process, the ETS model is also responsible for simulating the building load hydraulically. In order to create this boundary condition, the user must specify some initial parameters for the building's HVAC system. These include both the preferred supply temperature of the HVAC system and the preferred temperature drop across the building's heat exchanger. Combining these two assigned parameters with the historical building data, the ETS then simulates the building's thermal demands by changing the mass flow rate through the heat exchanger on the building side.

As the mass flow rate on the building side increases, the mass flow rate on the thermal network side also increases in order to match the increasing energy demands. This increase, in turn, raises the total mass flow rate required by the DHC system and as such, every ETS is part of a control network that interfaces with the EMC. This control network sends the ETS's varying mass flow rate back to the EMC. This data can then be used by the EMC controller to calculate the total mass flow rate required by the community for any given instance.

3.3.3 District Pipe

The District Pipe model calculates the thermal losses from the district pipes to the environment. Since LTTN have much lower supply temperatures than traditional DHC systems, and 5GDHC feature different pipe layouts, this model was crucial for determining how these design changes affect the systems total energy utilization. The model is based on an analytical approach completed by Wallentén [67]. Wallentén developed a series of analytical models for different district pipe configurations, including insulated single pipes, insulated double pipe and imbedded pipes. For each configuration, the multipole method was used to derive zero, first and second-order solutions to the heat transfer problems. The District Pipe model uses the second-order solution for single insulated pipes. This expression is outlined below, along with the relationship's defining parameters (Equation 3.1 to 3.3).

$$q = 2\pi\lambda_g(T_1 - T_o) \cdot h_1(H, r_{o,} \beta) \tag{3.1}$$

$$\beta = \frac{\lambda_g}{\lambda_i}\ln\left(\frac{r_o}{r_{\mathrm{i}}}\right) \tag{3.2}$$

$$h_1^{-1} = \left(\frac{2H}{r_o}\right) + \beta + \left[1 + \frac{(1+\beta)(1-2\beta)}{2(1-\beta)(1+2\beta)}\left(\frac{r_o}{2H}\right)^2 - \frac{3(1-2\beta)}{2(1+2\beta)}\left(\frac{r_o}{2H}\right)^4\right] \cdot \left[1 - \left(\left(\frac{2H}{r_o}\right)^2 - 3\frac{(1-2\beta)}{(1+2\beta)}\left(\frac{r_o}{2H}\right)^2\right)\frac{(1+\beta)}{(1-\beta)} - \frac{(1-2\beta)}{(1+2\beta)}\left(\frac{r_o}{2H}\right)^4\right]^{-1} \tag{3.3}$$

Where q is the pipe heat loss per unit length,
λ_g is the thermal conductivity of the ground,
λ_i is the thermal conductivity of the insulation,
T_1 is the temperature of the fluid in the pipe,
T_0 is the temperature at the ground surface,
h_1 is the heat transfer coefficient for the losses,
H is the buried pipe depth,
r_o is the outer radius of the pipe insulation,
r_i is the outer radius of the pipe,
β is a dimensionless parameter relating the ground's thermal conductivity to that of the pipe's insulation.

By providing the design parameters, λ_g, T_1, T_0, H, r_o, r_i, the total heat losses of the pipe can be calculated. Since T_1 changes over the length of the pipe, the analytical solution was integrated into the discretized pipe model, *DynamicPipe* from the Modelica base library. *DynamicPipe* solves a mass balance (3.4), a momentum balance (3.5), an energy balance (3.6) and a pipe friction equation (3.7) for multiple discretized sections within the specified pipe length. This integration allows the heat transfer calculations and the hydraulic analysis to be repeated throughout the length of the pipe while using a dynamic value for T_1.

$$\frac{\partial(\rho A)}{\partial t}+\frac{d(\rho A v)}{dx}=0 \tag{3.4}$$

$$\frac{\partial(\rho v A)}{\partial t}+\frac{d(\rho v^2 A)}{dx}=-A\frac{\partial p}{\partial x}-F_f-A\rho g\frac{\partial z}{\partial x} \tag{3.5}$$

$$\frac{\partial(\rho\left(u+\frac{v^2}{2}\right)A)}{\partial t}+\frac{\partial\left(\rho v\left(u+\frac{p}{\rho}\right)A\right)}{dx}= -A\rho v g\frac{\partial z}{\partial x}+\frac{\partial}{\partial x}\left(kA\frac{\partial T}{\partial x}\right)+\dot{Q}_e \tag{3.6}$$

$$F_f=\frac{1}{2}\rho v|v|fS \tag{3.7}$$

Where x is independent spatial coordinator parallel to the flow direction,
t is the simulation time,
$v(x,t)$ is the mean velocity,
p(x, t) is the mean pressure,
ρ(x, t) is the mean density,
$u(x,t)$ is the specific internal energy
$z(x)$ is the height over ground,
$A(x)$ is the area perpendicular to the flow direction (x),
k thermal conductivity of the working fluid,
$\dot{Q}_e$ thermal energy leaving the pipe (W/m),
F_f losses associated with pipe friction (N/m),
g is the gravity constant,
f is the friction factor,
S is the circumference.

3.3.4 Miscellaneous Models

3.3.4.1 District Pipes Variations

In total, two variations of the District Pipe model were created for ease of simulation. The first, *IsoPipe*, removes the heat transfer relationship outlined in 4.1.3 and instead assumes that the pipe is isothermal with no heat losses. This model was mainly used for control testing and model development.

The second model, *IsoBaricDistrictPipe,* removes the pressure loss model included in the base Modelica *DynamicPipe* model. This change was done to reduce the computation work required when modelling the energy consumption of large-scale district energy networks with numerous parallel piping connections.

3.3.4.2 BranchCap

The *BranchCap* model is used to balance the mass flow rates within the four-pipe DHC system. Since the EMC mass flow rate setpoint lags behind the actual demand at the ETSs, a small amount of additional fluid is supplied to the system in order to avoid cavitation at the supply pipe. If this buffer is not required, it flows through a balancing valve at the *BranchCap* and into the return pipe.

3.3.4.3 Interfaces

For the DHC models, two Modelica interfaces were created to simplify the simulation process. The first interface *ThermNet* connects all of the hydraulic models, including the ETS and district pipes to the EMC. This connection helps to simplify the control of the DHC system and is integral to implementing the mass flow control strategy outlined in 4.1.1. Additionally, the ThermNet connector also allows for all of the crucial simulation data to be transferred to the EMC model, and this makes analysis easier as it reduces the logging requirements of the compiler.

The second interface *ConNet* was created to simplify the analytical calculations done by the EMC's replaceable thermal generation equipment. This connector streamlines the data transfer between the four replaceable models and allows for easier analysis of the generation requirements.

3.4 UD-LTTN Models

For the modelling of UD-LTTN, both the EMC and ETS models were revised to include the design features of the UD-LTTN. Figure 16 outlines an example of the UD-LTTN modelling library when applied to a simple one building community. Similarly, to the DHC the modelling library, within the UD-LTTN library, the Energy Management Centre (EMC) represents the UD-LTTN system's centralized generation facility. The District Pipe models represent the system's piping network, and the Energy Transfer Stations (ETS) represents the connections between the building and the UD-LTTN system. Differing from the DHC library, since the UD-LTTN system provides both heating and cooling, two ETS models were created to support both thermal operations. Each version of the ETS model includes a heat pump which is configured to support singular thermal operation (either heating or cooling). Additionally, two Historical Building Data sources are included to provide both the ETS models with its own set of building load data.

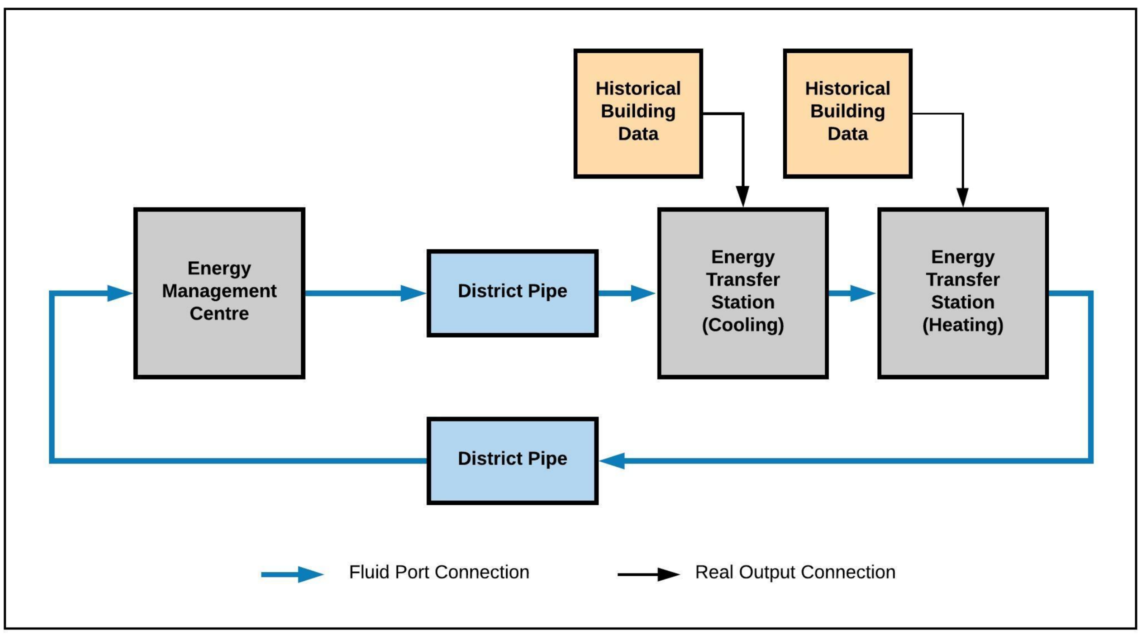

Figure 16 UD-LTTN Modelica Library Layout

3.4.1 EMC

Within the UD-LTTN framework, the EMC model includes many of the original design elements of the DHC EMC. These shared elements include the four replaceable equipment models and the fluids-based boundary condition. Where the UD-LTTN EMC differs from the DHC EMC is with regards to the mass flow rate.

Since the mass flow rate of the UD-LTTN is not a function of the total system demand, it does not require the same control system as the DHC model. Instead, the UD-LTTN EMC mass flow can be set by the user to a constant. This constant should be high enough to ensure that supply temperature is stable throughout the system regardless of the thermal demands of the community. Additionally, the UD-LTTN EMC model also allows the researcher to set the supply temperature of the EMC, but this parameter is also constrained by the design of the UD-LTTN as previously mentioned in 2.2.5.

3.4.2 ETS

The UD-LTTN ETS shares many base qualities of the DHC ETS. Specifically, it has a similar controller and sensory network as well as an identical base interface structure. However, it differs from the DHC ETS by integrating a heat pump model instead of a heat exchanger model. This heat pump model is taken from the open-source Modelica Library, AixLib [63] and simulates the heat pump's performance using a Carnot efficiency. Instead of relying on a datasheet from a real heat pump, this model uses performance data from an ideal Carnot cycle and applies a Carnot efficiency to the results (Equation 3.8). Although this Carnot efficiency can be calculated from experimental results, the simulated cycle will still follow the theoretical Carnot cycle.

$$COP = \eta_{hp} COP_{carnot} = \frac{\eta_{hp} T_{hs}}{T_{hs} - T_s} \tag{3.8}$$

Where COP the calculated coefficient of performance of the heat pump
η_{hp} is the Carnot efficiency of the heat pump,
COP_{carnot} is the Carnot coefficient of performance (for heating),
T_{hs} building side supply temperature (sink temperature),
T_s is the UD-LTTN supply temperature (source temperature).

For the UD-LTTN ETS model, the Carnot Efficiency for both the heating and cooling heat models (ETSC and ETSH) was derived from equipment datasheets. To accomplish this, two different sample equipment databases, consisting of multiple units within the same product line, were used to determine the average Carnot Efficiency across a variety of equipment sizes. For the ETSC models, this product line consisted of reversible heat pumps which were able to provide cooling at temperatures ranging from 5°C to 10°C with supply temperatures ranging from 15°C to 40°C. For the ETSH models, the sample product line consisted of booster heat pumps which were able to provide heating at temperatures ranging from 60°C to 71°C using a supply temperature ranging from 10°C to 30°C. These sample sizes resulted in Carnot Efficiencies of 0.462 and 0.351 for the heating and cooling machines, respectively. This integration of a Carnot cycle gave the ETSH and ETSC model flexibility and allowed the same model to be used with a variety of building types and sizes.

Similarly, to the DHC ETS, within the ETS model, the Carnot heat pump also calculates the pressure losses associated with the ETS. This functionality is optional, depending on the needs of the user. Additionally, the heat pump model also connects to a fluid interface that represents the building's HVAC system. In the future, this type of connection allows for the integration of Building Energy Models and gives the UD-LTTN library future flexibility.

3.5 Numerical Unit Testing

Before the comparative analysis, a series of analytical unit tests were completed for verification purposes. The models that underwent unit testing include, the ETSs (both DHC and UD-LTTN), the EMCs (both DHC and UD-LTTN) and the district pipe. In total, twenty-two unit tests were performed, with twelve tests being trivial cases and ten tests being analytical tests where the model's performance was compared against exact solutions. For the analytical tests, the exact solutions were performed by hand in order to provide external validation of the Modelica results. In summary, all five of the previously mentioned models passed all of their unit tests, and the complete results of this testing regime included in Appendix A.

3.6 Experimental Validation

After the unit testing, the Modelica library was used to model an experimental DHC case study in order to validate the analytical solution used to model the thermal pipe losses [67]. This case community consists of thirteen buildings within an approximate 1.2 km^2 area of an urban city centre. The buildings within the community include a high school, convention centre, municipal buildings, offices and multiple apartments. The case community's DHC is a four-pipe design, featuring a supply and return pipe for each of the heating and cooling processes. The design also includes a centralized heating plant as well as two decentralized plants for cooling operations.

For this case study, the heating system was modelled using the engineering drawings for the approximately eight-kilometre piping network as well as experimentally collected data for the community building loads and plant generation. The simulated system was modelled using the same operational parameters as the case community, with standard values used for the soil properties based on the community's local geology [68][69]. This experimental data was taken from all thirteen buildings at five-minute intervals over three months spanning from October of

2018 to January of 2019. In total, the community's demand for the three months consisted of 1092.6 MWh of heating and 129.5 MWh of cooling.

This Modelica model was then used to validate the analytical solution used within the thermal pipe loss model by comparing the model predicted generation requirements to the historical plant generation requirements. For the given system, the plant generation requirements are equal to the summation of the building demands and the thermal pipe losses within the system (Equation 3.9). Since the Modelica model, uses historical building data for the building demands, any error between the model predicted generation requirements and the historical plant generation requirements must stem from the pipe loss model. Using this methodology, the analytical solution for the thermal pipe losses was validated.

$$Q_{plant} = \sum_{1}^{n} Q_{building(i)} + Q_{pipe\ losses} \tag{3.9}$$

Where Q_{plant} is the total generation requirements at the centralized plant
$Q_{building(i)}$ is the heating demands for building [i],
$Q_{pipe\ losses}$ is the thermal pipe losses of the district heating system,
n is the number of buildings within the community.

3.6.1 Results

Figure 17 shows the hourly relative error between the predicted and historical energy generation requirements of the case community throughout the two different seasons (Equation 3.10). From this figure, during both seasons, the library consistently over predicts or under predicts the historical generation. In total, the average relative error for the fall season and winter seasons are 2.64% and 0.79% respectively (Equation 3.11).

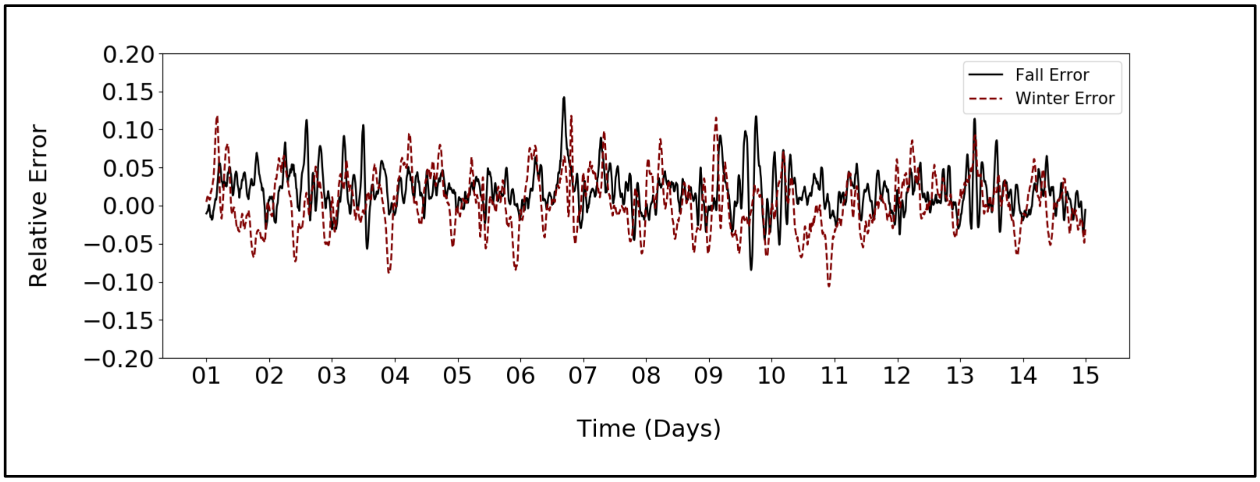

Figure 17 Relative Error Between Simulated and Experimental Generation Requirements

$$\delta Q = \frac{Q_m - Q_h}{Q_h} \tag{3.10}$$

$$\overline{\delta Q} = \frac{1}{n}\sum_{1}^{n} \left|\delta Q_{(i)}\right| \tag{3.11}$$

Where δQ is the relative error of model predictive generation requirements,
$\delta Q_{(i)}$ is the relative error of model predictive generation requirements at time step [i],
$\overline{\delta Q}$ is the average relative error of model predictive generation requirements,
Q_m is the model predictive generation requirements,
Q_h is the historical plant generation requirements,
n is the number of time steps within the simulation data set.

However, this percent error is largely the result of the centralized plant's delayed response to the building loads within the simulation (Figure 18). An alternative measure of accuracy is to compare the plant's total energy generation over the testing periods for both the predicted and the historical cases. This comparison indicates a relative error of 1.65% and 0.28% for the entirety of fall and winter periods, respectively. From this comparison, in both cases, the predicted generation surpasses the actual generation, which suggests that the *District Pipe* model is over predicting the losses present in the system.

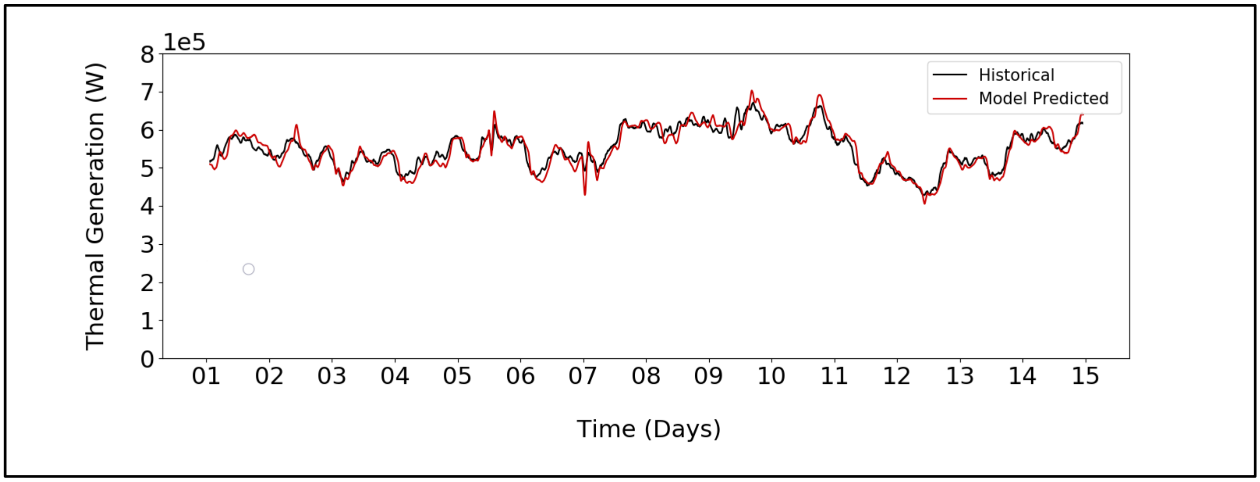

Figure 18 Historical Versus Model Predicted Generation Requirements

In general, the model predicted requirements follow the historical plant requirements closely, with sizable errors only occurring during periods of rapid change (days 2, 5, 7, 9, 10). These errors can be attributed to the EMC component model's system controller which has a delayed response to the demands within the community.

There are a variety of factors that could be contributing to this overestimation, including errors with the soil data used, differences in seasonal ground temperatures and differences between the as-built piping network and the engineering design drawings. These factors could potentially be addressed through further experimental measurements, which would allow for more accurate tuning of *DistrictPipe* model.

3.7 Example Model

To better explain the nature of the Modelica modelling process, Figure 19 highlights a section of the system model that was used for the experimental validation. This model simulates the DHC case study's performance and consists, thirteen energy nodes totalling in 11655 equations. Comparatively, the comparative analysis system models ranged as high as 43248 equations, and this because of the simultaneous simulation of both the DHC and UD-LTTN systems.

Within Figure 19, the blue lines represent connections between fluid interaces, while the black lines connecting to the orange *ThermNet* interfaces are the control connections that govern the operation of the EMC. Additionally this example also consists of EMC models, ETS models, IsoPipes models and DistrictPipes models in order to fully represent the DHC case study.

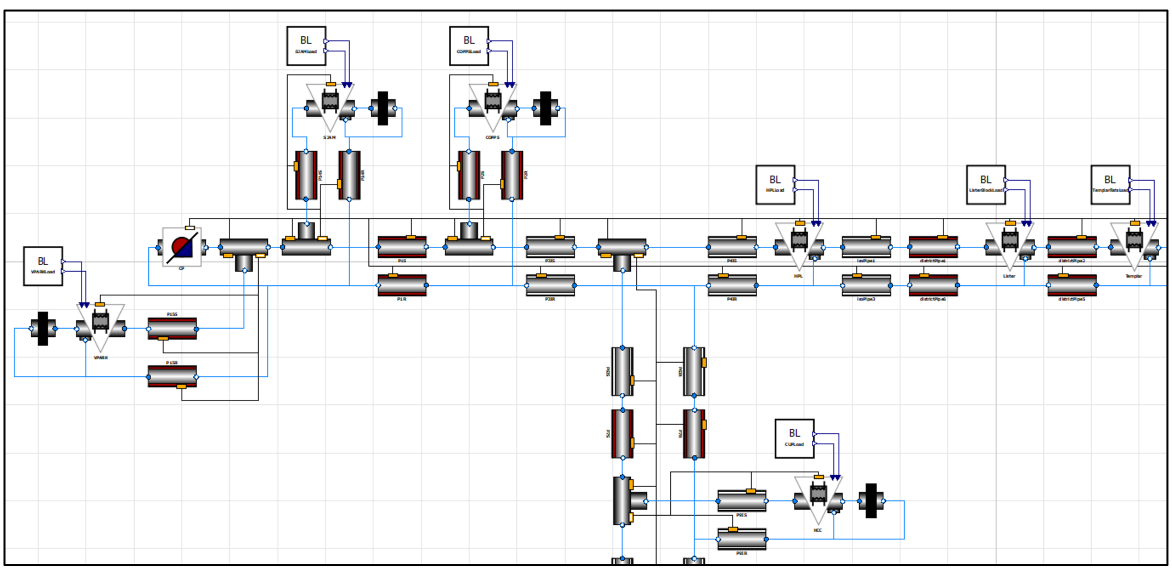

Figure 19 Sample Modelica System Model

Chapter 4

4. Comparative Analysis

For the comparative analysis buildings from the experimental DHC case study were chosen to create a case study community that was well suited to be served by either a UD-LTTN system or a larger DHC. Sections 4.1 and 4.2. describe the specifics of this case community, while Sections 4.3 and 4.4, outline the operational parameters chosen for both the DHC and the UD-LTTN systems. For the DHC, the operational parameters reflect the trends present in the historical building data and the literature. However, for the UD-LTTN, although some operational parameters are similar to the historical building data, additional analysis was done to determine the best operating parameters for T_s and $\dot{m}$.

4.1 Case Community

The case study community consists of nine of the thirteen buildings within the DHC case study community, and in total, these buildings occupy a 0.25 km^2 area (Figure 20). Similarly, to the validation community, the case community's building mix includes office buildings, municipal buildings, residential buildings and recreational facilities. As is shown in Figure 20, the community can be sectioned into two distinct campuses, and this was ideal for the UD-LTTN system as each campus can have its own series piping network. Within the community, four of the buildings within the Institutional Campus (B6 to B9) are connected to the DHC system by a singular ETS. This connection simplifies the analysis, as historical building data was only available at this singular ETS rather than at the individual buildings.

For both test cases, the same piping network specifications were implemented, with the series connections for the UD-LTTN following the same piping network layout of the traditional DHC (Figure 21). For both the UD-LTTN and DHC analysis, the district energy systems were responsible for all the heating and cooling demand within each of the buildings as well as the DHW demands of some of the buildings.

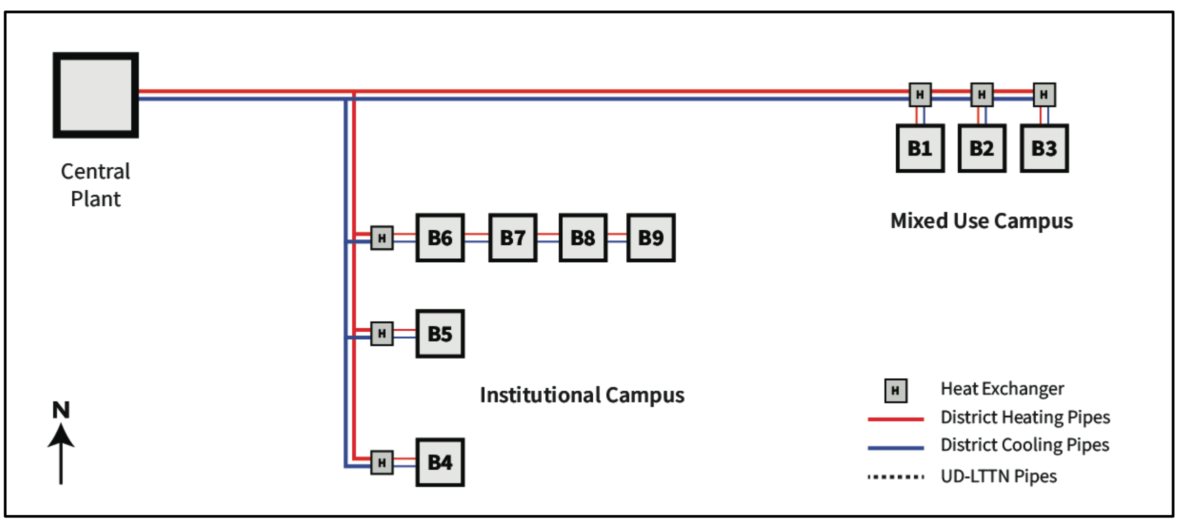

Figure 20 DHC System Design for Comparative Analysis Case Study

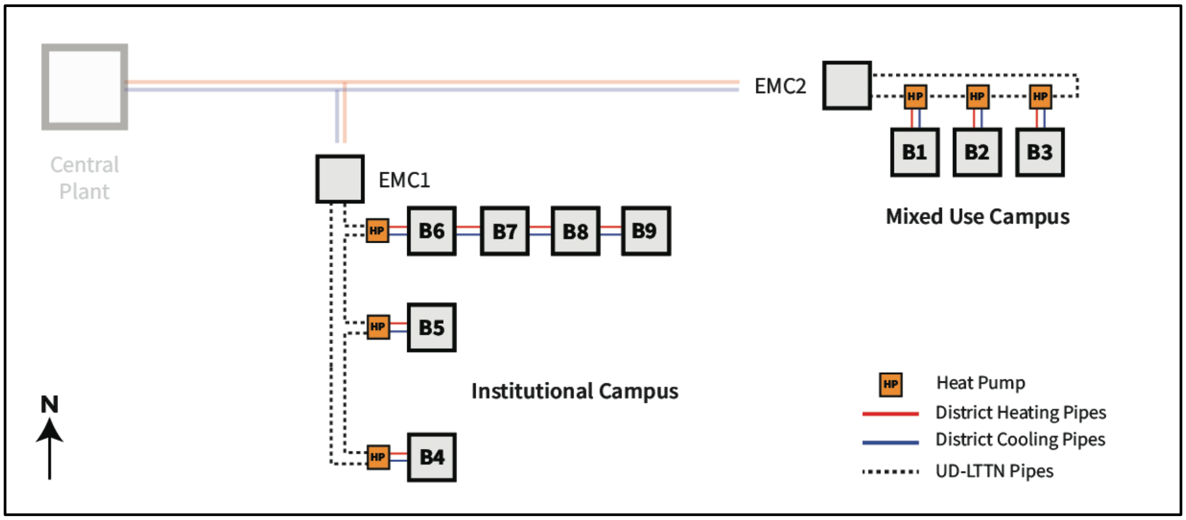

Figure 21 UD-LTTN System Design for Comparative Analysis Case Study

4.2 Case Study Period

To better assess the ability of the UD-LTTN system to integrate decentralized cooling, the comparative analysis considered four different two-week periods that had distinctively different generation requirements. During the Winter Period, the community was predominantly in heating mode, with loads equal to 91.65 MWh and 6.32 MWh for heating and cooling, respectively. These cooling demands occurred because of onsite refrigeration requirements at various buildings within the community. These asymmetrical requirements mean that the community had very little waste energy available from decentralized cooling operations and as such, makes this testing period a good reference case for the other seasons that have higher load diversity.

The second two-week period occurs during April. During this Spring Period, the same community has mixed generation requirements equal to 59.59 MWh and 10.25 MWh for heating and cooling, respectively. In this way, the Spring season will highlight the potential of Thermal Distributed Energy Resources (TDER). Additional to this Spring Period, a third Fall Period was modelled to assess whether there are similar trends between the two shoulder seasons (Table 1).

The fourth Summer Period includes two weeks in July. During this time frame, the community requires predominantly cooling with 62.40 MWh and 10.80 MWh of cooling and heating demands, respectively. During this period, the heating demands represent the DHW demands within the community. Due to these low heating demands, there was an excess of waste energy available for capture. Since most previous work on 5GDHC systems has focused on their ability to provide heating, this period will provide insight on whether 5GDHC systems are effective during periods of high cooling demands.

Table 1 Comparative Analysis Case Community Seasonal Demands

The heating and cooling demands for each building in the comparative analysis. All demands are displayed in MWh, and each season specifics the demands for the specific two-week testing period.

Summary		**Operation**	**Winter**	**Spring**	**Summer**	**Fall**
Mixed-Use Campus		Heating	15.71	9.70	0.48	8.03
		Cooling	1.26	1.99	10.30	1.96
Institutional Campus		Heating	75.94	49.89	10.32	36.92
		Cooling	5.06	8.26	52.10	8.22
Total		Heating	91.65	59.59	10.80	44.95
		Cooling	6.32	10.25	62.40	10.18
Mixed-Use Campus	**Type**	**Operation**	**Winter**	**Spring**	**Summer**	**Fall**
B1	Commercial	Heating	2.85	1.70	0.18	1.40
		Cooling	1.16	1.71	4.07	1.79
B2	Residential	Heating	1.51	0.71	0.20	0.63
		Cooling	0.01	0.23	1.02	0.08
B3	Commercial	Heating	11.35	7.29	0.10	6.00
		Cooling	0.09	0.05	5.21	0.09
Institutional Campus	**Type**	**Operation**	**Winter**	**Spring**	**Summer**	**Fall**
B4	Institutional	Heating	20.13	13.96	8.14	8.53
		Cooling	0.0	0.18	11.14	0.69
B5	Commercial	Heating	11.71	6.39	1.81	4.97
		Cooling	1.06	1.88	5.10	0.28
B6 to B9[*]	Mixed	Heating	44.10	29.54	0.35	23.42
		Cooling	4.0	6.20	35.86	7.25

4.3 DHC Parameter Selection

For the District Heating and Cooling case, the system operated at temperatures consistent with the 3rd Generation District heating and traditional district cooling systems. The district supply temperatures, T_{hs} and T_{cs} were set to 75°C and 5°C respectively. Although this value of T_{hs} is lower than some traditional 2nd Generation District heating system, this temperature was chosen so that both the DHC and UD-LTTN cases had the same building side temperature requirements. For the DHC systems, the mass flow of both systems fluctuated with demand in order to maintain consistent temperature differences across the ETS heat exchangers.

In both the DH and DC systems, similar pipe designs as those featured in the DHC case study were used to model the system. For the district heating network, a 125mm nominal diameter pre-insulated steel pipe size was used, with an outside pipe diameter of 141.3mm and an insulation thickness of 50mm. For the district cooling network, a 200mm nominal diameter uninsulated D11 HDPE pipe was used, with an outside pipe diameter of 219.2mm. At the EMC, an ideal natural gas boiler and electric chiller were used to provide all heating and cooling generation respectively.

4.4 UD-LTTN Parameter Selection

4.4.1 General Parameter Selection

For the UD-LTTN system, additional analysis was done to determine the optimum values for T_s and $\dot{m}$ that would ensure stable operation for the six heat pumps within the system (Figure 21). However, other operational parameters such as the temperature requirements at the buildings (T_{hs} and T_{cs}) and the pipe design parameters did not require additional analysis. For T_{hs} and T_{cs}, the same temperatures used by the DHC networks were selected (75°C and 5°C respectively). This selection ensures that both test cases were identical in terms of their total energy requirements. For the piping network design, the same pipe specification used for the heating pipe is used for both

UD-LTTN networks (125mm nominal diameter, 50mm insulation thickness). By keeping these design specifications consistent, the comparative analysis can be used to assess the potential for retrofitting the existing piping network to meet the UD-LTTN system standard. Additional testing was also done using the cooling pipe (200mm nominal diameter uninsulated D11 HDPE pipe) in order to assess the potential for uninsulated pipes with UD-LTTN systems. At the EMC, an ideal natural gas boiler and electric chiller were used to provide all heating and cooling generation respectively.

4.4.2 UD-LTTN Supply Temperature Analysis

Since the UD-LTTN incorporates decentralized heat pumps at the ETSs, additional considerations must are required when calculating T_s. As in the DHC system, T_{hs} and T_{cs} are both crucial parameters, as they are the preferred supply temperatures required by the building HVAC system. However, T_s which is the temperature of the unidirectional piping network, must also be determined. Since in the unidirectional design, the thermal network provides for both heating and cooling operations, T_s must be complementary to both operations. As such, the optimal value of T_s is a function of the COPs of the heat pumps, the demands within the system and the system's electrical and thermal generation capacity.

These relationships are evident in Equation 4.1, which is a costing function for determining the optimal value of T_s based on a community's current demands (in-depth derivation present in Appendix B).

$$X = \begin{cases} \sum_{1}^{n} \eta_{Th}\left(X_{h(i)} - X_{c(i)}\right) + \eta_e X_{e(i)}, & X_{h(i)} > X_{c(i)} \\ \sum_{1}^{n} \eta_e X_{e(i)}, & X_{h(i)} = X_{c(i)} \\ \sum_{1}^{n} \eta_{Tc}\left(X_{c(i)} - X_{h(i)}\right) + \eta_e X_{e(i)}, & X_{h(i)} < X_{c(i)} \end{cases} \tag{4.1}$$

Where:

$$X_{c(i)} = \left(Q_{cb(i)} + \frac{Q_{cb(i)}\left(T_s - T_{cs(i)}\right)}{\eta_{cc(i)} T_{cs(i)}}\right) \qquad X_{h(i)} = \left(X_{hb(i)} - \frac{Q_{hb(i)}\left(T_{hs(i)} - T_s\right)}{\eta_{hc(i)} T_{hs(i)}}\right)$$

$$X_{e(i)} = \left[\frac{Q_{hb(i)}\left(T_{hs(i)} - T_s\right)}{\eta_{hc(i)} T_{hs(i)}} + \frac{Q_{cb(i)}\left(T_s - T_{cs(i)}\right)}{\eta_{cc(i)} T_{cs(i)}}\right]$$

Where X is the costing parameter being minimized
$Q_{hb(i)}$ is the heating demands for building [i],
$Q_{cb(i)}$ is the cooling demands for building [i],
$T_{hs(i)}$ is the preferred hot water supply temperature for building [i],
$T_{cs(i)}$ is the preferred cold water supply temperature for building [i],
T_s is the supply temperature of the UD-LTTN,
η_e is the electrical costing parameter,
η_{Th} is the thermal costing parameter for heating generation,
η_{Tc} is the thermal costing parameter for cooling generation,
$\eta_{cc(i)}$ is the Carnot Efficiency for the cooling heat pump at building [i],
$\eta_{hc(i)}$is the Carnot Efficiency for the heating heat pump at building [i],
n is the number of buildings within the community

Equation 4.1 calculates the instantaneous system-wide cost of energy based on the current building demands, Carnot cycles and Carnot efficiencies. Using this equation, the optimal value of T_s can be calculated dynamically to minimize X for any given time step.

The most important aspects of this equation are the costing parameters η_e and η_T (η_{Tc} and η_{Th}). These parameters weigh the cost of electric generation against the cost of thermal generation. When $\eta_e > \eta_T$, it means that the UD-LTTN system should reduce its total electrical requirements as it is the most costly generation source. When $\eta_T > \eta_e$, the opposite is true and thermal generation, either heating or cooling operations should be minimized. These costing parameters could be used to describe generation costs in a variety of units, including operations costs ($), carbon emissions (Mt/CO2) and primary energy values (W).

To determine the ideal of T_s for the UD-LTTN case study, Equation 4.1 was used to find the optimal temperature set point of the case community during the entirety of the testing period. This optimization was completed in Modelica with the historical building data from the case community used as dynamic values for $Q_{hb(i)}$ and $Q_{cb(i)}$. Once this data was interfaced with Modelica, a parameter sweep of T_s was completed using Equation 4.1 to determine the supply temperature that minimizes the primary energy consumption of the system for each time step.

Since this analysis focused on reducing the primary energy consumption of the system, the costing parameters η_T and η_e had to be calculated based on the system's primary energy efficiency. For heating and cooling generation, this calculation was done using equipment efficiencies and the primary energy factors of the equipment's energy sources (Table 4). For both heating and cooling operations, η_T would have specific values (η_{Tc} and η_{Th}) and both of these parameters were calculated based on general equipment efficiencies.

However, for the electrical costing parameter, η_e is a much more complex calculation. Ideally, η_e would be a dynamic calculation that would depend on the current electrical resources supplying the UD-LTTN. Since this dynamic information was not available, information on Ontario's electrical generation mix was used to determine the average annual value of η_e. This information is presented in Table 2 and 3. Table 2 describes the different efficiencies and primary energy factors used for the different types of electricity generation within Ontario [61][62]. Table 3 describes the generation mix of these sources within Ontario's electrical grid [72]. Using this generation mix and efficiency, η_e could be calculated as an average value throughout the year. This calculation resulted in the case community valuing electrical generation more than thermal, with values of 2.35, 0.87 and 1.05 being used for η_e, η_{Tc}, and η_{Th} respectively (Table 4).

Table 2 Generation Efficiencies Used to Determine the Electrical Costing Parameter

	Nuclear	***Natural Gas***	**Hydro**	***Wind***	***Solar***
Efficiency	33%	40%	100%	100%	100%
Primary Energy Factor	3.0	2.5	1.0	1.0	1.0

Table 3 Generation Mix Used to Determine the Electrical Costing Parameter

	Generation Mix					
Case	*Nuclear*	*Natural Gas*	*Hydro*	*Wind*	*Solar*	η_e
Ontario	60%	10%	24%	6%	< 1%	2.35

Table 4 Efficiencies Used to Determine the Thermal Costing Parameter

Case	*Equipment*	*Energy Source*	*Efficiency*	*Source PE Factor*	η_T
η_{Th}	Boiler	Natural Gas	95%	1.0	1.05
η_{Tc}	Air Source Chiller	Electricity	COP = 2.7	2.35	0.87

Using these costing parameters, the Carnot efficiency of the UD-LTTN ETS models, and the case community's parameters for T_{hs}, T_{cs}, $Q_{hb(i)}$ and $Q_{cb(i)}$, a parameter sweep of T_s was performed using Equation 4.1. For this parameter sweep, the T_s was varied from 15°C to 25°C using a 0.10°C step. These maximum and minimum temperature constraints ensured that the optimal supply temperature was within the acceptable temperature range for both the UD-LTTN ETS models (as described in 3.3.2). Although the true maximum range is 10°C to 30°C, since T_s will fluctuate throughout the network, a 5°C buffer was included at both limits of the range. From this parameter sweep, the optimal loop temperature was calculated, and Figure 23 and Figure 22 illustrate the results of this optimization for both the Institutional and Mixed-Use campuses.

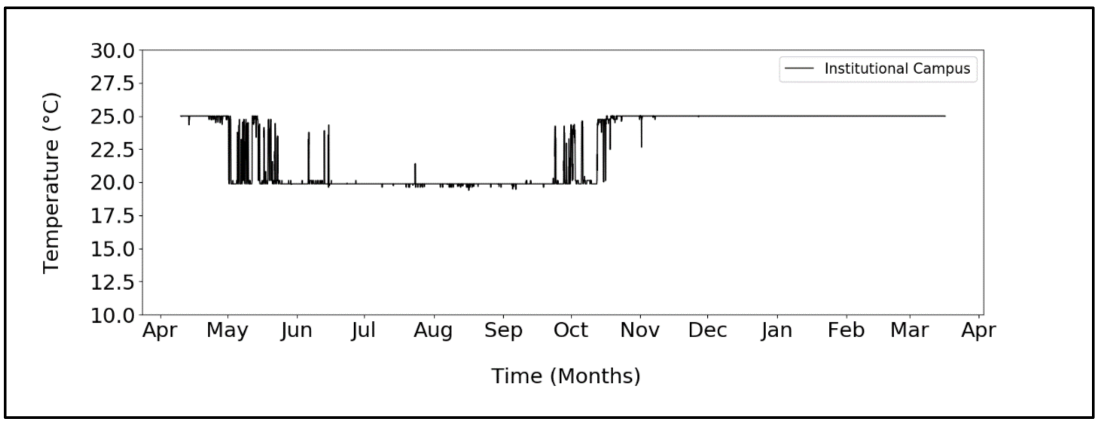

Figure 22 Institutional Campus Supply Temperature Analysis

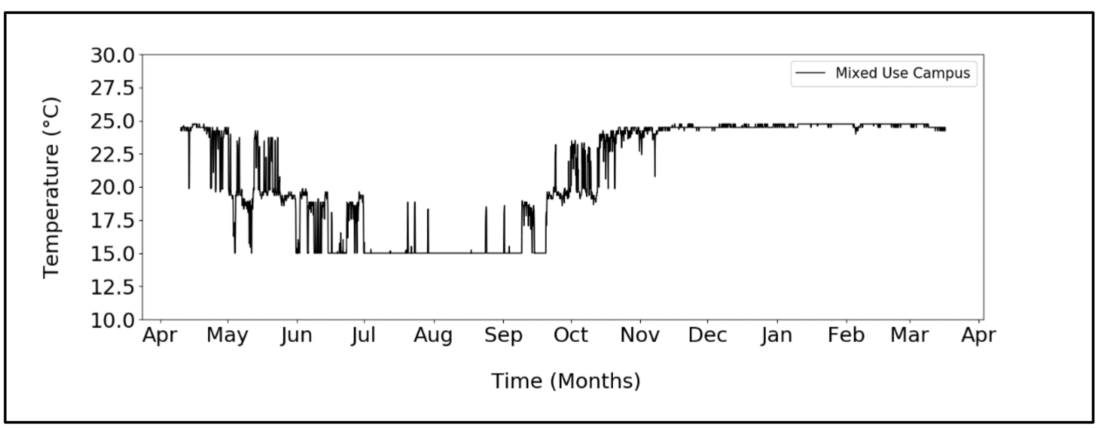

Figure 23 Mixed Use-Campus Supply Temperature Analysis

From the optimization, since electrical energy is more costly in terms of primary energy, the system operates at two temperature extremes in order to reduce electrical consumption. In general, during the winter, the system should operate at the highest set point (25°C) to increase the performance of the heating heat pumps. This trend is true for the majority of the winter, with very few fluctuations being seen from the 25°C set point.

Comparatively during the summer, due to the DHW demands within the community and the increased efficiency of the cooling heat pumps, T_s does not stay at a lower limit of 15°C. Instead during the summer T_s fluctuates within a lower range of 15°C to 20°C in order to maximize the performance of both the DHW and the cooling operations. This trend is especially prominent in the Institutional Campus, which has much higher DHW demands than the Mixed-Use Campus.

For both the winter and summer seasons, it is important to understand how the fixed efficiency of the thermal generation equipment impacts the supply temperature optimization. Specifically during the summer, since the COP of the air source chiller is fixed, the optimization does not consider how changing T_s can impact the performance of the air source chiller. In reality, higher T_s set-points may lead to increased air-source chiller performance, and this could, in turn, lead to the temperature optimization predicting a higher optimal supply temperature. However, since the Modelica library uses fixed efficiencies, the same constants were used for temperature optimization so that the overall analysis was consistent.

During the shoulder seasons, it is clear from Figure 23 and Figure 22 that multiple temperature fluctuations are occurring as the system alternates from being predominantly cooling to predominantly heating. Therefore, it was determined that for the UD-LTTN system to operate efficiently, T_s should fluctuate dynamically throughout the simulation. As such, for all four seasons, the optimum supply temperatures calculated using Equation 4.1 were used within the model as a dynamic set point. Although the EMC maintained this dynamic setpoint as a supply temperature, the temperature was allowed to free float throughout the piping network.

4.4.3 Loop Mass Flow Rate Analysis

For the UD-LTTN, the mass flow rate is no longer a function of community-level demand but instead a crucial parameter for system stability. After each ETS, the temperature of the supply pipe changes proportionally to the demands within the building. If the building has high cooling demands, the temperature in the supply pipe will rise, since the energy from the building is added to the supply water. For high heating demands, the temperature in the supply pipe will fall, since energy is removed from the water. If these fluctuations are too large, it can reduce the heat pump performance of other buildings connected to the piping network. To maintain consistent performance, the mass flow rate within the loop must be set high enough so that T_s is consistent throughout the entirety of the piping network. This setpoint can be determined by accounting for the maximum energy transfer to or from the piping network, as indicated by Equation 4.2 (in-depth derivation showcased in Appendix C).

$$\dot{m} = \frac{Q_{max}}{C_p \Delta T_{max}} \tag{4.2}$$

$$where \quad Q_{max} = MAX([Q_{\max(s)}], [Q_{\max(h)}], [Q_{\max(c)}]) \tag{4.3}$$

$$where \quad Q_{\max(s)} = \sum_{1}^{n} \left| \left(Q_{hb(i)} - \frac{Q_{hb(i)}\left(T_{hs(i)} - T_s\right)}{\eta_{hc(i)} T_{hs(i)}} \right) - \left(Q_{cb(i)} + \frac{Q_{cb(i)}\left(T_s - T_{cs(i)}\right)}{\eta_{cc(i)} T_{cs(i)}} \right) \right| \tag{4.4}$$

$$where \quad Q_{\max(h)} = \sum_{1}^{k} Q_{hb(i)} - \frac{Q_{hb(i)}\left(T_{hs(i)} - T_s\right)}{\eta_{hc(i)} T_{hs(i)}} \tag{4.5}$$

$$where \quad Q_{\max(c)} = \sum_{1}^{j} Q_{cb(i)} + \frac{Q_{cb(i)}(T_s - T_{cs(i)})}{\eta_{cc(i)} T_{cs(i)}} \tag{4.6}$$

Where $\dot{m}$ is the minimum mass flow rate with the UD-LTTN,
ΔT_{max} is the maximum allowable change in T_s,
C_p is the specific heat capacity of water,
Q_{max} is the maximum energy transfer to or from the UD-LTTN,
$Q_{hb(i)}$ is the heating demands for building [i],
$Q_{cb(i)}$ is the cooling demands for building [i],
$T_{hs(i)}$ is the preferred hot water supply temperature for building [i],
$T_{cs(i)}$ is the preferred cold water supply temperature for building [i],
T_s is the supply temperature of the UD-LTTN,
$\eta_{cc(i)}$ is the Carnot Efficiency for the cooling heat pump at building [i],
$\eta_{hc(i)}$is the Carnot Efficiency for the heating heat pump at building [i],
n is the number of buildings within the community
k is the number of buildings consecutively connected to piping network requiring heating
j is the number of buildings consecutively connected to piping network requiring cooling

While Equation 4.2 calculates $\dot{m}$ based on Q_{max}, Equation 4.3 compares three potential measures of Q_{max}. These three theoretical measurements use both the Carnot cycle and a Carnot efficiency to calculate different energy transfers rates to and from the thermal loop based on building thermal demands.

In order to assess all potential energy transfers, these measurements would have to be calculated multiple times for various building combinations within the community. From this calculated sample, the largest value of Q_{max} would be selected, as this value would result in the greatest change in T_s, and as such should be used to calculate $\dot{m}$. These three measurements include $Q_{\max(s)}$, $Q_{\max(h)}$, and $Q_{\max(c)}$. Whereas $Q_{\max(h)}$ and $Q_{\max(c)}$ focus on individual and consecutive building thermal operations, $Q_{\max(s)}$ focuses on system-wide energy implications.

Consecutive thermal operations occur when there are multiple buildings in series performing the same thermal operation. In these scenarios, T_s can be drastically changed by the cumulative effect of these consecutive building connections. To account for this cumulative effect, $Q_{\max(h)}$

and $Q_{\max(c)}$ calculate the total energy transferred by consecutive buildings performing either heating (4.5) or cooling (4.6). In cases when there are no consecutive buildings, k and j would be set to one. This, in turn, would negate the summation and would result with $Q_{\max(h)}$ and $Q_{\max(c)}$ equaling an array composed each building's singular energy transfer requirements.

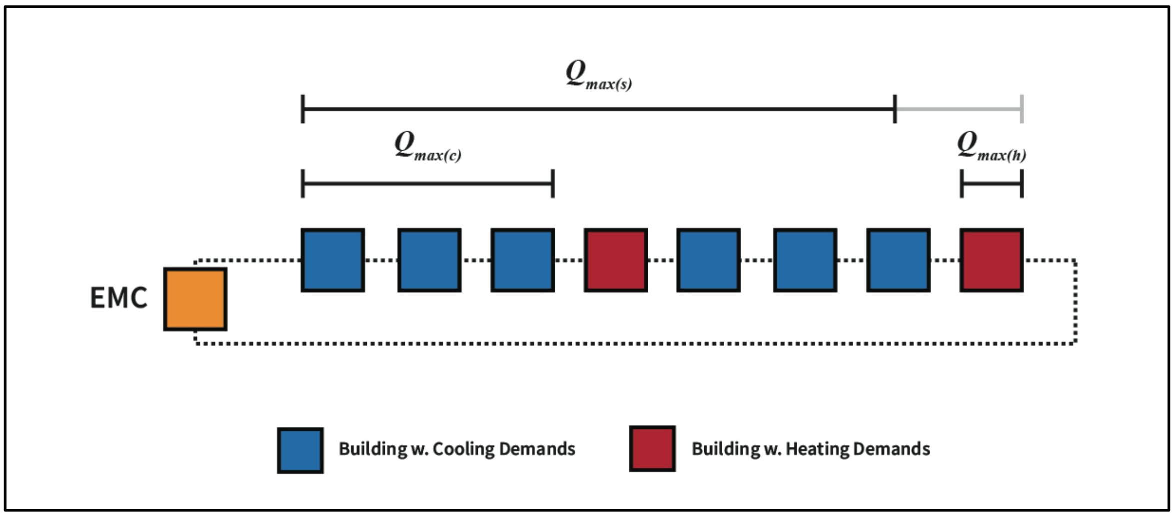

Figure 24 Mass Flow Analysis Case Community

The quantity $Q_{\max(s)}$ represents the total energy requirements of the system (4.4). $Q_{\max(s)}$ is the net energy transfer either into or out of the thermal network. It is an important measure of Q_{max}, especially during periods that predominantly require one thermal operation (either heating or cooling). To explain this concept, consider the case community in Figure 24.

In this hypothetical case community, during the Fall season six buildings require cooling, and two buildings require heating. In this case $Q_{\max(c)}$ would be a large value as there are two unique groups of consecutive three-building sets that require cooling. However, it would be incorrect to use $Q_{\max(c)}$ to calculate $\dot{m}$ as it would not accurately account for the temperature drop by the end of the seventh building. Instead $Q_{\max(c)}$ would only account for the temperature drop across one of the three-building groups and this would lead to an underestimation of $\dot{m}$. In this case, it is more appropriate to consider $Q_{\max(s)}$ which would be the larger of the three values and would provide a more stable result for $\dot{m}$.

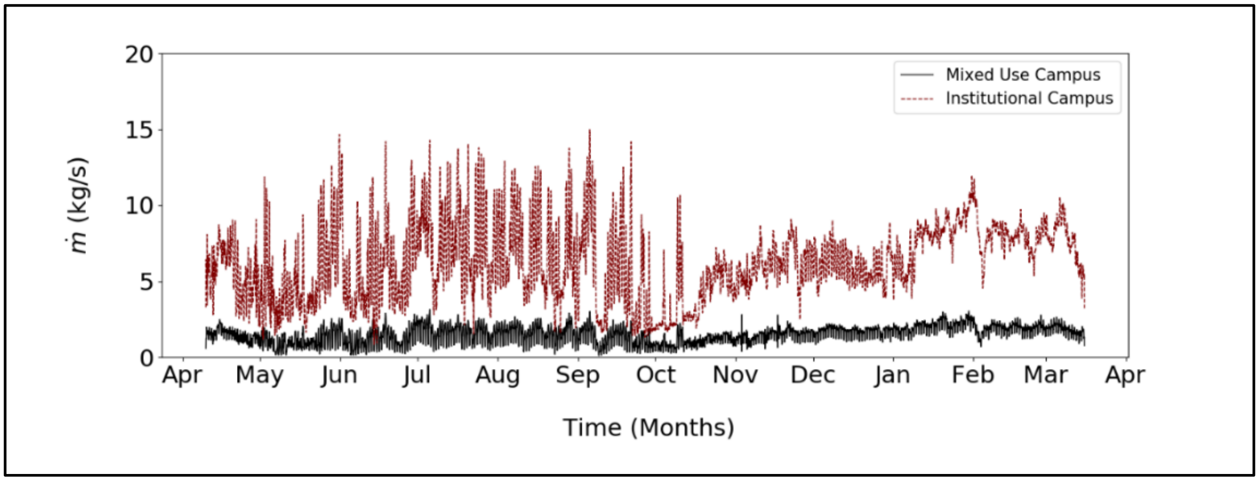

Figure 25 Mass Flow Analysis Results for both the Institutional and Mixed-Use Campuses

By using $Q_{\max(c)}$, $Q_{\max(h)}$, $Q_{\max(s)}$ and the Carnot efficiency of the UD-LTTN ETS models to calculate $\dot{m}$, T_s can be regulated to stay within ΔT_{max}. This process was completed for both UD-LTTN systems to constraint T_s to be within 5°C of its set point. Figure 25 displays the results of this process. Overall, the Institutional Campus mass flow ($\dot{m}_1$) was much higher when compared to the Multi-Use Campus mass flow ($\dot{m}_2$) and this is mainly because of the community's higher system-wide thermal demands. For the entirety of the testing period, $\dot{m}_1$ ranged from 0.74kg/s to 15.10kg/s while $\dot{m}_2$ ranged from 0.09kg/s to 3.32kg/s.

With this analysis complete, it was decided that for the comparative analysis $\dot{m}_1$ and $\dot{m}_2$ would be set to 18.5kg/s and 4.0kg/s respectively. These higher set points ensured an adequate safety factor of at least 20% was included to accommodate any differences in heat pump performance between theoretical Carnot analysis and the systems simulated performance. Based on the results from this analysis, and the previous analysis regarding T_s, the parameters presented in Table 5 were used for UD-LTTN for the comparative analysis.

Table 5 UD-LTTN Comparative Analysis Parameters

For this simulation T_{cs1} and T_{cs2}, represent the preferred chilled water supply temperatures for each campus building. T_{hs1} and T_{hs2}, represent the preferred hot water supply temperatures for each campus building. $\dot{m}_1$, and $\dot{m}_2$ are the mass flow set points of each UD-LTTN system. T_{s1} and T_{s2} are the dynamic, optimal supply temperature set points of each UD-LTTN system.

	Institutional Campus				**Mixed-Use Campus**			
Season	T_{hs1} *(°C)*	T_{cs1} *(°C)*	$\dot{m}_1$ *(kg/s)*	T_{s1} *(°C)*	T_{hs2} *(°C)*	T_{cs2} *(°C)*	$\dot{m}_2$ *(kg/s)*	T_{s2} *(°C)*
Winter	75	5	18.5	$T_{opt1}(s)$	75	5	4.0	$T_{opt2}(s)$
Spring	75	5	18.5	$T_{opt1}(s)$	75	5	4.0	$T_{opt2}(s)$
Summer	75	5	18.5	$T_{opt1}(s)$	75	5	4.0	$T_{opt2}(s)$
Fall	75	5	18.5	$T_{opt1}(s)$	75	5	4.0	$T_{opt2}(s)$

Chapter 5

5. Results and Analysis

5.1 LTTN Characterization of Thermal Distributed Energy Resources

To understand how UD-LTTN systems (Figure 26) can utilize heat pumps to recover energy from Thermal Distributed Energy Resources, comparisons were made between a UD-LTTN and DHC system (Figure 27). For each of the four testing periods, the dynamic energy generation requirements and the impact of distributed thermal energy resources are discussed. Additionally, comparisons are made regarding total energy utilization, carbon emissions, peak electrical requirements, pipe thermal losses and pressure losses.

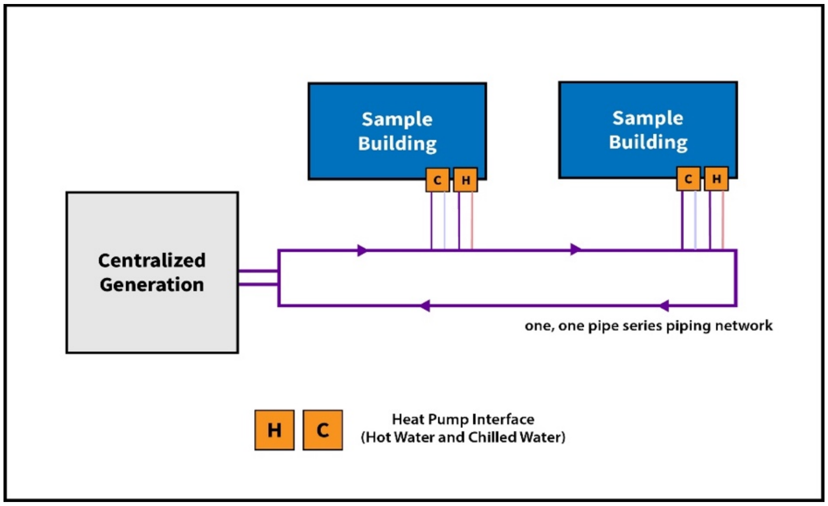

Figure 26 Unidirectional Low Temperature Thermal Network (UD-LTTN) Configuration

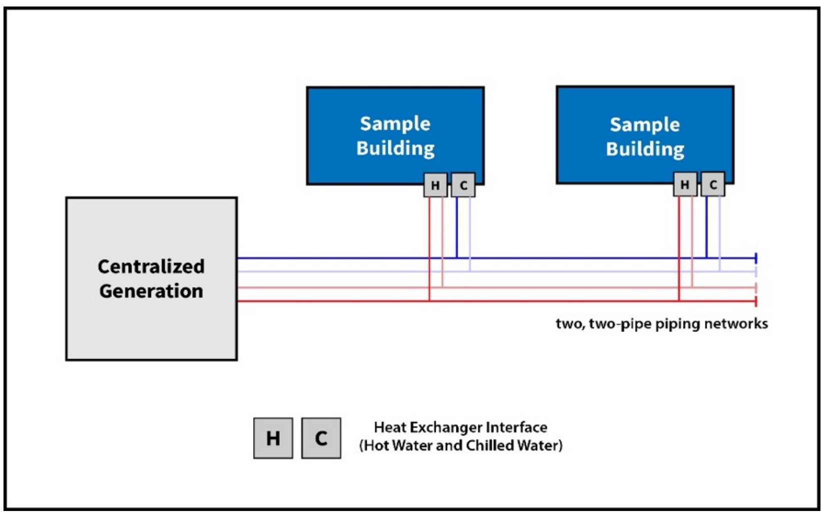

Figure 27 District Heating and Cooling (DHC) System configuration

5.2 Energy Generation Requirements

The dynamic energy generation requirements for each testing period are discussed below. These trends are indicative of each season's dynamic energy consumption and indicate how the integration of TDERs can reduce system-wide generation requirements. These trends include the energy requirements specific to each generation operation, as well as the total energy consumption for each two-week period (Table 6). This total includes the electrical pumping power requirements for each system.

For each test, the energy consumption for both the DHC and UD-LTTN system is presented in

Table 6. Additionally, Table 6 also provides insight into the performance of the UD-LTTN system, with the last column highlighting the normalized energy intensity of the UD-LTTN system when compared to the DHC system (UD/DHC). For each of the Spring, Fall and Winter seasons, it was found that the UD-LTTN system required less energy than the DHC system. This increased energy utilization resulted from increased energy sharing and the reduction of thermal pipe losses. The summer season, however, indicated an increase in energy utilization of 33% and this anomaly will be discussed in further detail throughout the following sections.

Table 6 Comparative Analysis Energy Generation Requirements Results (Ontario)

The heating, cooling, and electrical generation requirements for both the DHC and UD-LTTN systems over the four different testing periods. Each value is expressed in MWh with the following distinctions made between energy sources: NG – MWh of natural gas heating, ELEC – MWh of electricity.

	DHC System			**UD-LTTN System**				
Season	*Heating (NG)*	*Cooling (ELEC)*	*Total*	*Heating (NG)*	*Cooling (ELEC)*	*ETS Power (ELEC)*	*Total*	*UD/DHC*
Units	(MWh)	(MWh)	(MWh)	(MWh)	(MWh)	(MWh)	(MWh)	
Winter	94.9	1.7	96.5	46.8	0.0	39.6	87.0	0.90
Spring	62.5	3.6	66.1	24.4	0.1	26.4	51.5	0.78
Summer	13.2	24.2	37.4	0.0	27.4	21.9	49.9	1.33
Fall	47.4	3.9	51.3	15.9	0.2	19.9	36.6	0.71

Beyond the specific energy generation requirements, graphs of the normalized energy generation requirements were also created to analyze the dynamic trends that occurred over the two-week periods. For each of these graphs, the generation data for DHC and UD-LTTN systems was normalized with respect to the largest energy generation requirement that occurred during the specific testing period. This allows for comparisons to be made between the two systems during the same season; however, inter-seasonal comparisons are not possible using these plots.

5.2.1 Winter Season

During the winter season, since the system was predominantly in heating, there was only a small amount of waste energy available for capture (Figure 28 and Figure 29). Although the system did eliminate the need for centralized cooling, this effect is relatively insignificant compared to the system-wide increase in electrical energy requirements. The UD-LTTN system did, however, lower total energy utilization requirements by 10% due to the sharing of thermal energy, and by decreasing the thermal pipe losses of the system. Specifically, the UT-LTTN system reduced thermal pipe losses by 88% during the winter period, which resulted in 2.86MWh of energy savings.

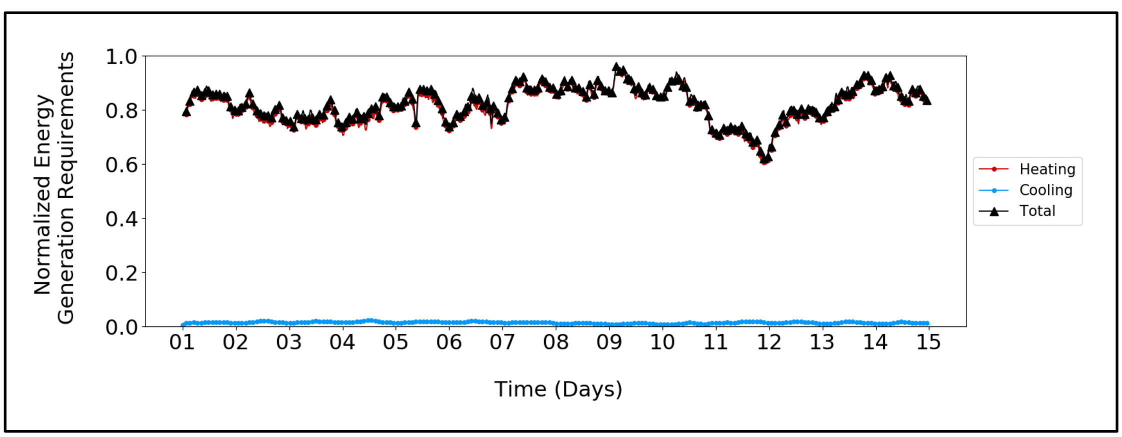

Figure 28 DHC System Dynamic Energy Comparisons - Winter

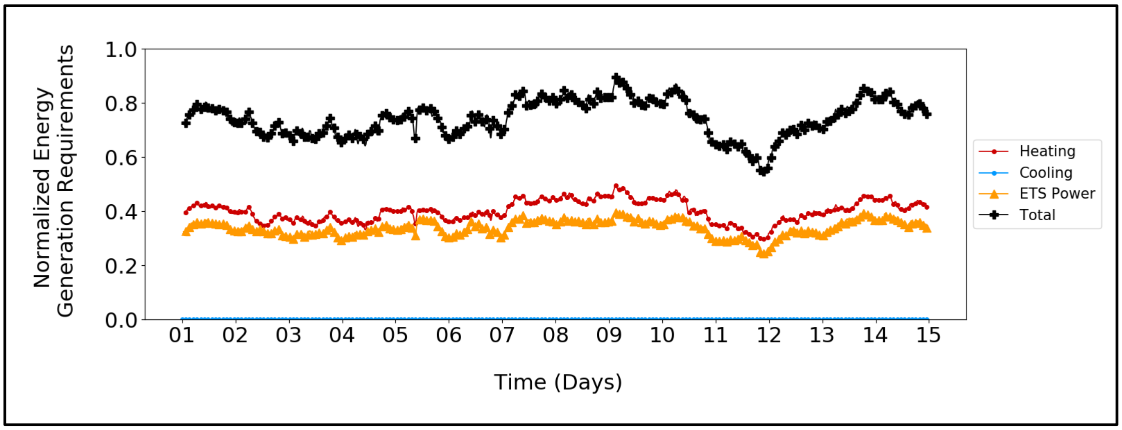

Figure 29 UD-LTTN System Dynamic Energy Comparisons - Winter

5.2.2 Spring Season

During the spring season, the first week of operations is reflective of the winter period with predominantly high heating demands (Figure 30 and Figure 31). However, during the second week, the heating demands decrease, and this reduction helps to increase the efficiency of the UD-LTTN system. During days seven to fourteen, the UD-LTTN is almost able to fully eliminate the need for centralized cooling due to the temperature drop induced by the heating process. This, in turn, results in a lower rate of total energy consumption for this period, which is reflected by the Total curve in Figure 31.

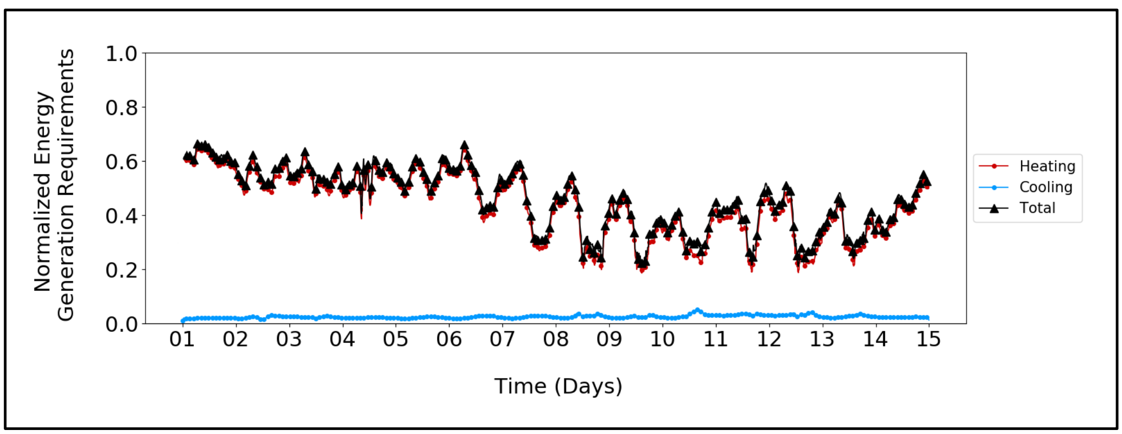

Figure 30 DHC System Dynamic Energy Comparisons - Spring

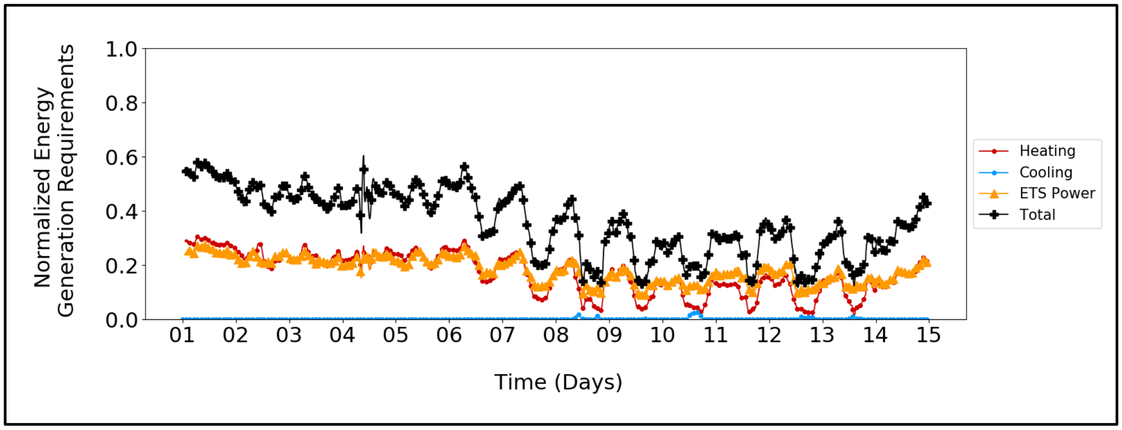

Figure 31 UD-LTTN System Dynamic Energy Comparisons - Spring

5.2.3 Summer Season

During the summer testing period, the UD-LTTN uses significantly more energy than the DHC system. In total, the UD-LTTN system is 33% more energy-intensive than the traditional system (Table 6). The main reason for this inefficiency is the system's design and the thermal generation equipment used.

When the system is predominantly in cooling, every decentralized heat pump within the system is using electrical work to transfer heat from the buildings to the thermal network. When this energy is transferred to the thermal network, the total energy added to the thermal network is equal to both the heat removed from the building and the electrical energy used by the heat pump. During these periods, due to the low heating demands, there is no demand for this additional energy, and therefore, the EMC is responsible for conditioning the thermal network. At the EMC, an air source chiller is then used to transfer the heat from the thermal loop and to the environment, thus balancing the network temperature.

In this way, more electrical work is required to remove the same amount of heat when compared to a traditional DHC system (Figure 32 and Figure 33). This inefficiency is an unexpected result of decentralized heat pump integration and will be discussed in more detail during the thematic analysis.

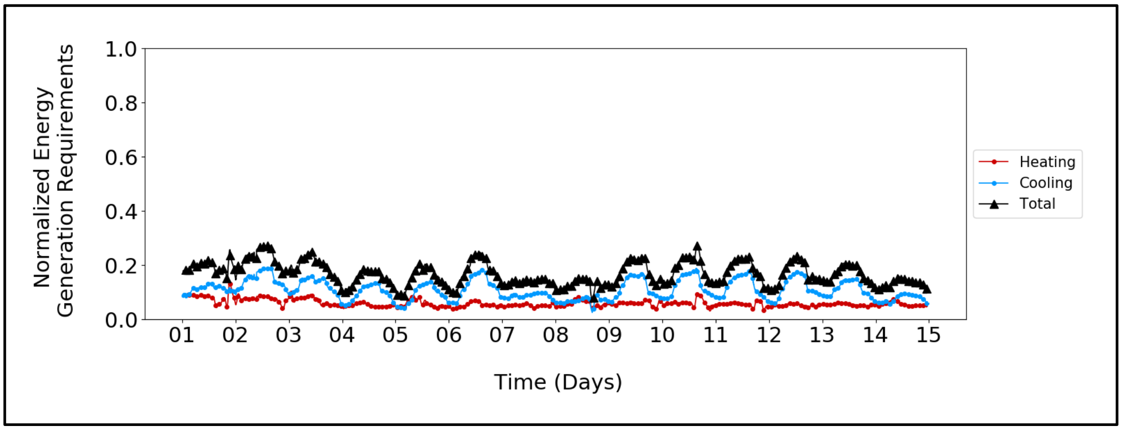

Figure 32 DHC System Dynamic Energy Comparisons - Summer

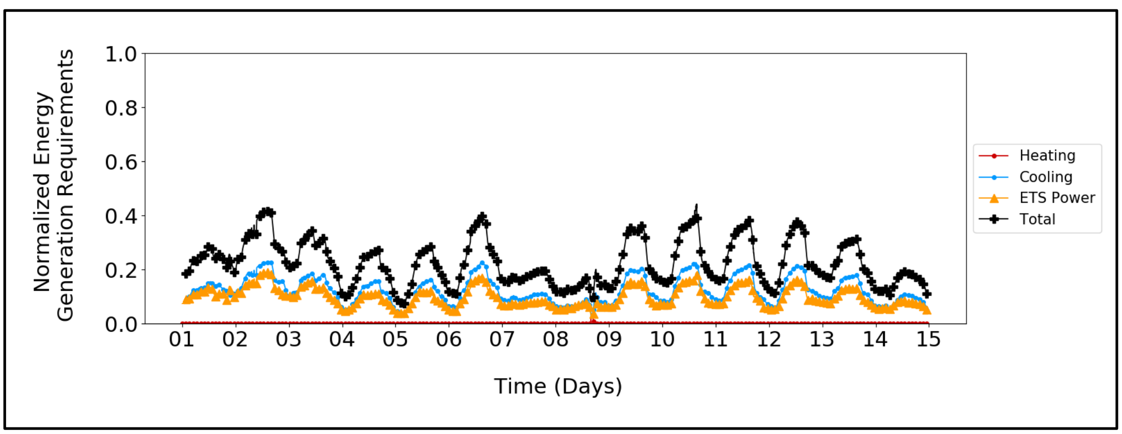

Figure 33 UD-LTTN System Dynamic Energy Comparisons - Summer

5.2.4 Fall Season

During the Fall period, the community experienced higher baseload cooling demands than the Spring, and this reduced the centralized heating generation and total energy consumption of the UD-LTTN system (Figure 34 and Figure 35). Additionally, the dynamic results of this season indicate that there are a few days during the testing period that require centralized cooling (days one, two and six).

This centralized generation is of interest, as during these periods, energy is being rejected to the environment using the EMC. However, right after this rejection occurs, as the day turns to night, the Fall season experiences an increase in heating demand. This cycle of cooling demands during the day and heating demands during the night is common during the shoulder season and represents an interesting opportunity for the introduction of thermal energy storage. This storage could capture the excess waste energy present in the system during the day, and use this stored energy to provide heating during the night, thus reducing the centralized generation requirements of the system [37].

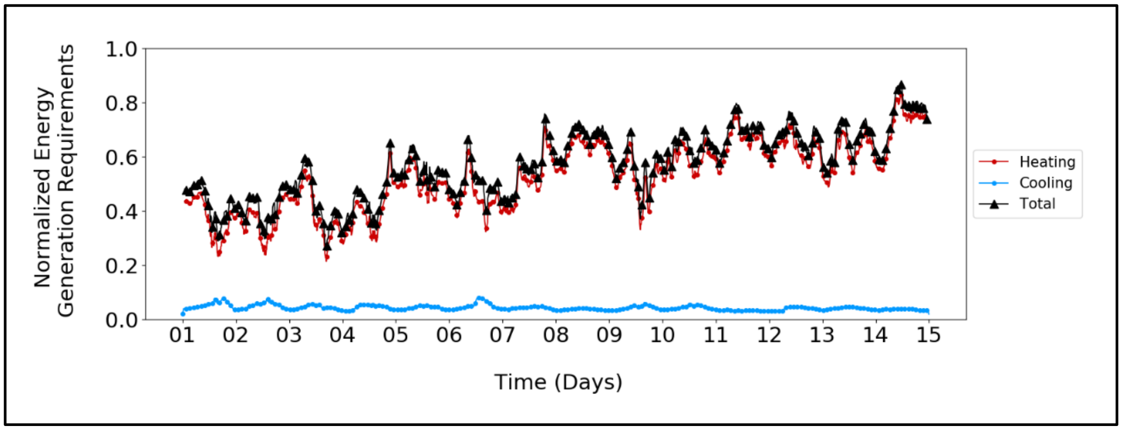

Figure 34 DHC System Dynamic Energy Comparisons - Fall

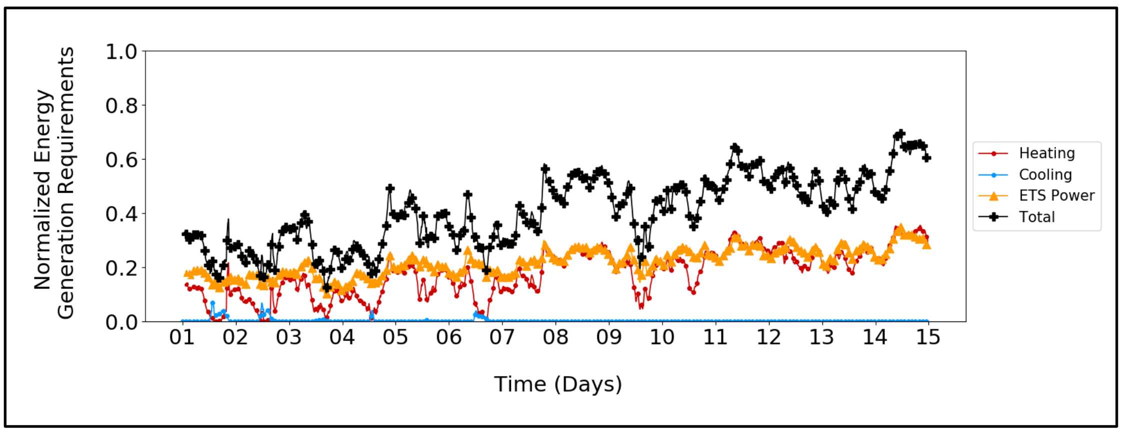

Figure 35 UD-LTTN System Dynamic Energy Comparisons - Fall

5.3 Carbon Emission Trends

For carbon emissions, comparisons were made between both the DHC and UD-LTTN system based on the systems natural gas consumption and electrical generation requirements. Since the UD-LTTN system has high electrical generation requirements, it was important to consider the carbon emissions from a variety of electrical generation sources.

With this mind, comparisons were made between the two systems using six different electrical grid archetypes. In addition to an Ontario case study, five different case studies were considered with grids that ranged from 20% to 100% supplied by renewable generation (20R, 40R, 60R, 80R and 100R) (Table 7). For each case, the carbon emissions from electrical generation were calculated using standard equipment efficiency and greenhouse gas equivalencies taken from the literature (Table 8) [71][73][74].

Table 7 Carbon Emission Analysis Electrical Grid Cases

	Generation Mix		
Case	*Nuclear*	*Natural Gas*	*Renewables*
20R	0%	80%	20%
40R	0%	60%	40%
60R	0%	40%	60%
80R	0%	20%	80%
ON	60%	10%	30%
100R	0%	0%	100%

Table 8 Efficiency, Emission Factor and Higher Heating Value used in the Carbon Emission Analysis

Natural Gas Generation Efficiency	***Natural Gas CO_2 Emission Factor (kg/m^3)***	***Natural Gas HHV (MJ/m^3)***
40%	1.88	39

For each case and testing period, the UD-LTTN was compared to the DHC performance and normalized with regards to the DHC performance (Table 9). In general, the Ontario case study shows that the UD-LTTN can reduce carbon emission significantly with an average reduction of 46% present across all four seasons. This reduction is the direct result of lowering the centralized heating generation requirements of the system by capturing waste energy from decentralized cooling loads. It is also the result of integrating decentralized heat pumps that reduced the system's natural gas generation requirements by subsidizing the thermal generation process with relatively carbon-free electrical work from Ontario's grid.

For the rest of the cases, similar trends are present. However, it is worth noting that as the electrical grid's renewable generation capacity decreased lower than 60%, the UD-LTTN becomes more carbon-intensive during the peak seasons (Winter 40R, Summer 60R). This trend continues, and for the 20R case, all seasons become more carbon-intensive than the traditional DHC system. This seasonal decrease further supports the conclusion that the UD-LTTN is more efficient during the shoulder seasons when there is mixed thermal demands and the sharing of energy from decentralized cooling demands.

Finally, it is important to note that for the 100R case, the UD-LTTN reduced carbon emissions by on average 69%. This reduction includes a 100% reduction during the Summer season and a 51% reduction during the winter. This reduction during the Winter season is further evidence that the UD-LTTN system may have a role to play when it comes to the electrification and decarbonization of residential and commercial heating.

Table 9 Comparative Analysis Normalized Carbon Emission Production

This table displays the different carbon emission intensities for various testing periods (Winter, Spring, Summer, Fall) and electrical grid cases (20R, 40R, 60R, 80R, ON, 100R). For each scenario, the UD-LTTN system's total carbon emissions were normalized by the DHC system's total carbon emissions. As such, scenarios with carbon emission intensities less than 1.0, indicate cases where the UD-LTTN was able to reduce the total carbon emissions of the community.

Season	20R	40R	60R	80R	ON	100R
Winter	1.28	1.09	0.90	0.70	0.60	0.49
Spring	1.11	0.94	0.77	0.59	0.49	0.39
Summer	1.60	1.49	1.32	0.98	0.64	0.00
Fall	1.02	0.87	0.70	0.53	0.43	0.33

5.4 Peak Electricity Requirements

As previously shown, 5GDHC systems increase the total electrical demands for the system due to the integration of decentralized heat pumps. As such, it is important to assess how 5GDHC systems increase daily peak electrical demands (weekdays from 7:00-19:00). Table 10 shows the results of this assessment. This comparison considers all the electricity generation requirements present in the system, including cooling operations, heat pump operations and pumping power. For each season, the peak electrical generation requirements of the UD-LTTN system were normalized with regards to the peak electrical load of the DHC during the Summer season. The Summer season was chosen as a control because the peak electrical demands of the DHC system occur during the summer when the system is predominantly in cooling.

Table 10 Comparative Analysis Normalized Peak Electrical Requirements

System	Winter	Spring	Summer	Fall
DHC	0.07	0.14	1.0	0.16
UD-LTTN	1.48	0.92	2.08	0.75

From this analysis, the UD-LTTN installation would double the case community's peak electricity generation demands. This increased demands would be necessary during the peak seasons, with the Winter and Summer seasons requiring an additional 48% and 108% peak capacity, respectively. For the Spring and Fall seasons, the UD-LTTN system had much higher peak electrical requirements than the DHC system. However, it still required less electricity generation than the annual DHC Summer peak. It is also worth noting that the exceptionally high peak electrical requirements for the UD-LTTN during the Summer is another externality of having excess waste energy recovery during the summer months. As previously mentioned, this inefficiency could be addressed by a few potential UD-LTTN design changes, and this will be explained in further detail during the thematic analysis.

5.5 Pipe Losses

Since one of the motivations to shifting to 5GDHC systems is to lower the thermal pipe losses from high-temperature district energy systems, it is important to analyze the thermal losses of the UD-LTTN system. Table 11 showcases the normalized thermal pipe loss rates for the UD-LTTN when compared to the DHC system. For each case, the total pipe losses of both UD-LTTN installations (Institutional Campus and Mixed-Use Campus) were normalized with respect to the total pipe losses of the DHC system. This comparison was performed for all four periods of operation, and additional testing was done to compare the performance of the UD-LTTN system when outfitted with the uninsulated cooling pipe. In general, when outfitted with the insulated heating pipe, the UD-LTTN reduced system-wide pipe losses by 88% during the peak Winter period. This reduction in thermal losses is partly responsible for increasing the UD-LTTN system's efficiency during the Winter season, even when there are minimal decentralized waste energy resources. The Spring and Fall periods exhibited similar results and indicated an average reduction of 89% and 90%, respectively. Additionally, the Summer period had exceptionally low thermal pipe losses because of the small temperature difference between the ground and the supply temperature during the summer season.

Table 11 Comparative Analysis Normalized Thermal Pipe Losses

Piping Type	Winter	Spring	Summer	Fall
DH Pipe	0.12	0.11	0.01	0.10
DC Pipe	0.59	0.55	0.04	0.47

Additional analysis was also performed to assess the performance of the UD-LTTN when outfitted with the cooling pipe. This 200mm nominal diameter uninsulated D11 HDPE pipe has the potential to be more economical and easier to install than the insulated steel district heating pipe [17]. Overall it was found that even with the cooling pipe, the UD-LTTN was still more efficient than the DHC system. The uninsulated cooling pipe losses were 41% less than the DHC system during the winter period, with an average reduction of 59% over the four periods analyzed.

In summary, these tests are indicative that the decreased supply temperature of the UD-LTTN can potentially improve system performance by lowering the thermal pipe losses of the system. However, the exact impact of this improvement depends on electrical consumption and total energy utilization of the decentralized heat pumps within the system.

5.6 Pumping Power Considerations

An investigation was done during the Summer period to compare the pumping power requirements of each DHC design. The previous mass flow analysis (4.3.3) indicated that from June to August, both the Institutional and Mixed-Use UD-LTTN networks required high mass flow rates to stabilize the performance of the system. These increased flow requirements are because of the high cooling demands during this period as well as the decentralized heat pumps which add energy to the thermal network during the cooling process. Due to these increased energy demands, during the summer season, both UD-LTTN systems had to operate at their highest mass flow set point.

As calculated above, these points were 18.5 kg/s for the Institutional Campus and 4.0 kg/s for the Mixed-Use Campus. These setpoints were significantly higher than the District Cooling system, which averaged a flow rate of approximately 6.90 kg/s and ranged from 3.12 kg/s to 10.63 kg/s (Figure 36). However, these high setpoints for $\dot{m}_1$ and $\dot{m}_2$ were effective, with T_s being maintained within 5°C of the supply temperature set point for both Campuses (Figure 37).

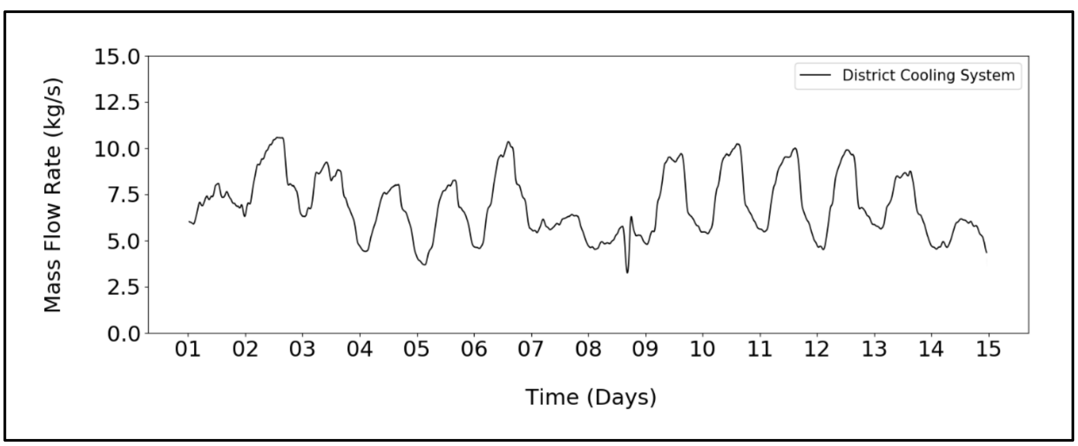

Figure 36 Instantaneous Mass Flow Rate for the DHC System during the Summer Period

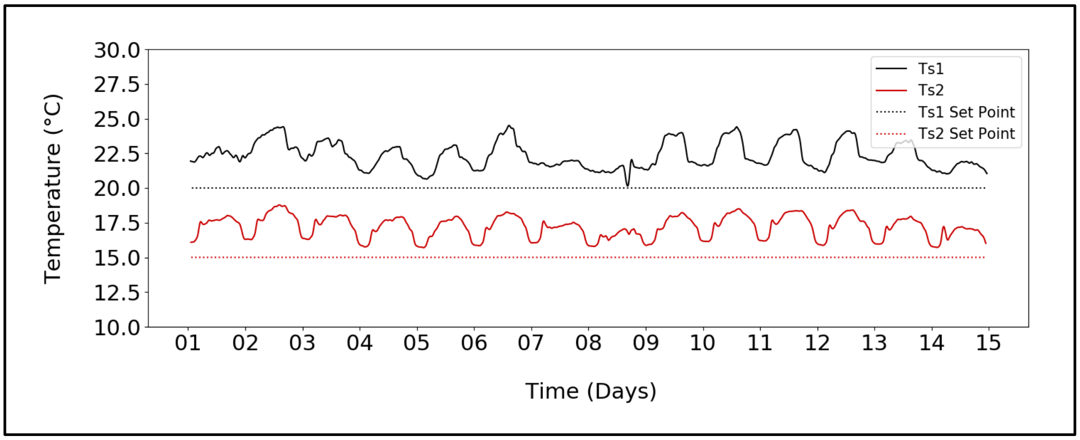

Figure 37 Instantaneous Return Temperature For Both UD-LTTN systems

This increase in mass flow rate means that the UD-LTTN system requires a higher pump discharge pressure than the DC system, and in turn has higher pumping power requirements. For the same pump efficiency of 0.80, this increase in discharge pressure leads to the UD-LTTN requiring 556.8 kWh of electrical energy compared to the DC systems 5.6 kWh requirements over the two-week testing period for the Ontario case study. This increase is significant and equivalent to 1.49% of the total energy requirements of the DHC system during the Summer period. Overall, these findings indicate that retrofitting existing DHC piping networks to the UD-LTTN system standard may not be possible unless the piping specifications support the higher flow rate requirements.

5.7 Summary

Using the Modelica library described in Chapter 3, an analysis was done to compare the performance of both UD-LTTN and DHC systems for the same case study. This analysis found that through lowering the supply temperature of the system and sharing energy between TDERs, the UD-LTTN system can reduce the total energy utilization of the community when compared to the DHC system.

Specifically, these benefits allowed the UD-LTTN system to reduce total energy utilization by up to 29% and reduce community carbon emissions by up to 100% during some of the Summer periods. However, these carbon emissions savings were only realized when the UD-LTTN system was supplied with 100% renewable electrical generation. This dependency on renewable electricity is an unfortunate externality of the integration of decentralized heat pumps and led to decreasing reductions in carbon emission for electrical grids that had less than 50% renewable generation.

Additionally, the integration of decentralized heat pumps exposed an interesting artifact in the design of the EMC within the UD-LTTN system. This design shortcoming centred on the use of an air-source chiller during the Summer season in the EMC as a heat rejection source, which led to UD-LTTN system utilizing 33% more energy during this period than the DHC system.

These findings, although specific to this case study, are indicative of broader themes within the area of UD-LTTN system design. In the next chapter, these thematic areas will be further explored to determine how they relate more generally to UD-LTTN system design.

Chapter 6

6. Thematic Analysis

This chapter builds on the findings of the Comparative Analysis and extends the results to the broader field of UD-LTTN system design. Specifically, this chapter describes an energy balance analysis that was completed to highlight the different thermodynamic mechanisms that impact UD-LTTN system performance. Then an analytical solution was developed that facilitates the easy identification of communities that have an ideal mix of TDERs. These communities would be the model candidates for UD-LTTN system applications, as the mix of TDERs would maximize the potential for energy sharing. Finally, an energy generation analysis was completed that compares the different types of energy generation that can potentially increase UD-LTTN system performance.

6.1 Energy Balance Analysis

From the comparative analysis, it is clear that the UD-LTTN system has the potential to increase total energy utilization and decrease carbon emissions under existing conditions of Ontario's electricity grid and in systems comprising of 60+% carbon-free electricity sources. These trends were evident during the Fall, Spring and Winter seasons during which the UD-LTTN system reduced energy utilization by up to 28%. These reductions are the result of two main benefits that have discussed throughout the literature review and the comparative analysis. The first benefit is how the integration of TDERs can reduce the total energy utilization of the community through energy sharing. The second is how lowering the temperature of the thermal network, can reduce the thermal pipe losses of the system, which in turn lowers the total energy utilization of the system.

Additional to these benefits, a shortcoming in this case study's design is also discussed from an energy balance perspective. Specifically, if an air source chiller is used at the centralized EMC location, it leads to increased energy utilization during periods of predominantly cooling. This finding was an unexpected externality of the integration of decentralized heat pumps.

6.1.1 The Energy Sharing Benefit

The energy sharing benefit is the primary reason why the Fall and Winter seasons were able to reduce the total energy utilization of the community by on average 26%. To better understand this benefit, consider the two energy balances illustrated in Figure 38 and Figure 39. During the Fall and Spring seasons, the DHC system provides for each building's energy demands using two separate pieces of generation equipment. This equipment must generate enough energy to provide for the building demands and the pipe losses associated with each piping network (Equation 6.1).

Comparatively, during the Fall and Spring seasons, the UD-LTTN system has lower thermal energy requirements because of the sharing of thermal energy. Since the UD-LTTN system provides for both heating and cooling demands using the same piping network, the energy captured from the cooling demands can be used to provide for the heating demands (Equation 6.2). It is this sharing of energy resources that leads to the 26% reduction in total energy utilization for the UD-LTTN system. This benefit is made possible by the integration of decentralized heat pumps and the increased electrical demands contributing to the useful heating of the UD-LTTN system (Equation 6.2).

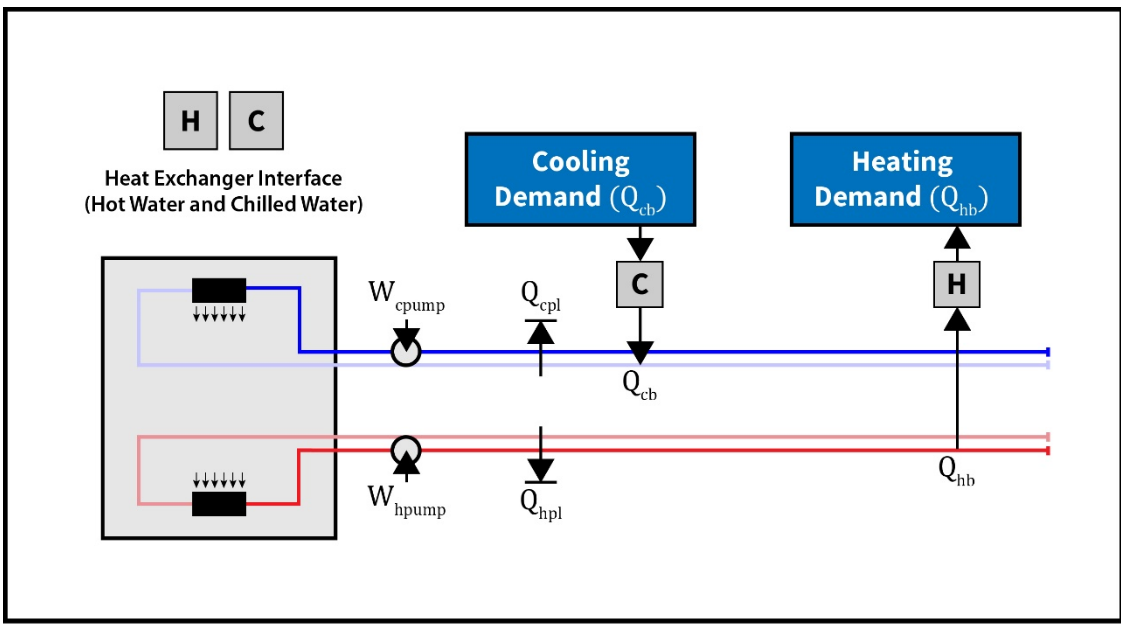

Figure 38 District Heating and Cooling System Energy Balance (Energy Sharing)

Descriptions and a full energy balance included in Equation 6.1

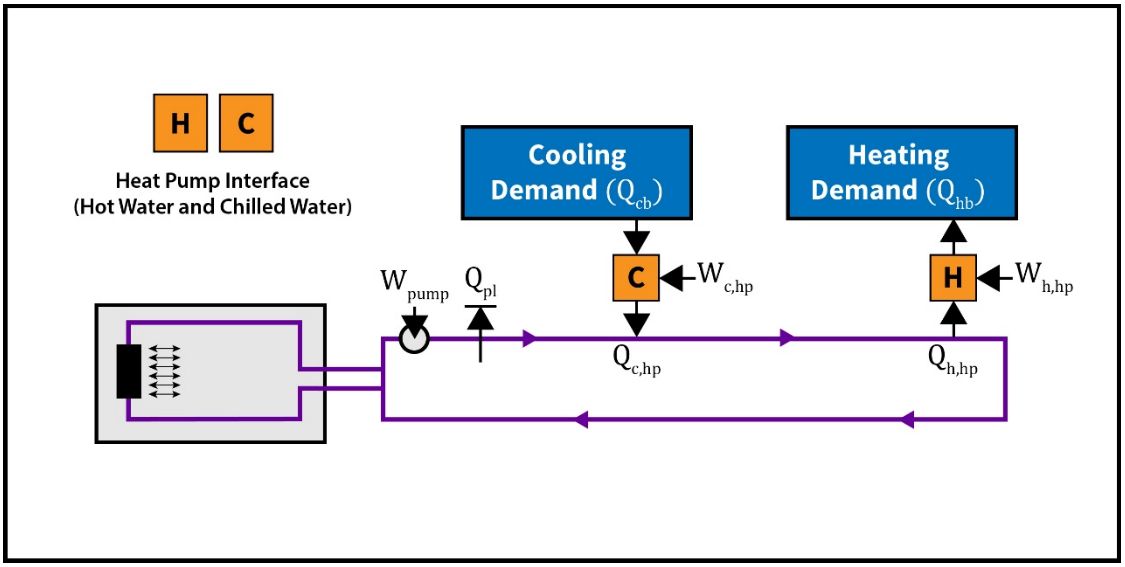

Figure 39 Unidirectional Low Temperature Thermal Network Energy Balance (Energy Sharing)

Descriptions and a full energy balance included in Equation 6.2

$$E = \left(Q_{hb} + Q_{hpl}\right) + (Q_{cb} + Q_{cpl}) + (W_{hpump} + W_{cpump}) \tag{6.1}$$

$$E = \left(\left|Q_{h,hp} - Q_{c,hp}\right| + Q_{pl}\right) + (W_{pump} + W_{h,hp} + W_{c,hp}) \tag{6.2}$$

Where E is the total energy requirements of the system,
Q_{hb} is the heating demands within a building,
Q_{cb} is the cooling demands within a building,
Q_{hpl} is the thermal pipe losses from the heating piping network,
Q_{cpl} is the thermal pipe losses from the cooling piping network,
Q_{pl} is the thermal pipe losses from the UD-LTTN piping network,
$Q_{h,hp}$ is the energy transferred to or from the heating heat pump,
$Q_{c,hp}$ is the energy transferred to or from the cooling heat pump,
$W_{h,hp}$ is the work required by the heating heat pump,
$W_{c,hp}$ is the work required by the cooling heat pump,
W_{hpump} is the work required by the circulation pump for the heating piping network,
W_{cpump} is the work required by the circulation pump for the cooling piping network,
W_{pump} is the work required by the circulation pump for the UD-LTTN piping network,

6.1.2 The Low-Temperature Benefit

The second benefit of the UD-LTTN system is its low supply temperature, which allows it to reduce its system-wide thermal pipe losses. This benefit is prominent during the Winter season when the UD-LTTN system utilized 10% less energy than the DHC system.

Figure 40 and Figure 41 describe the DHC and UD-LTTN system energy balances for this scenario. During this period, the UD-LTTN system and the DHC are supplying the same demands, with the community requiring predominantly heating. This demand mix means that unlike the previous example, there are no cooling demands within the community, which would enable energy sharing. Instead, the system's increased energy efficiency is the result of the UD-LTTN system having lower thermal pipe losses than the DHC system. Referring to Equation 6.3 and 6.4, since Q_{pl} is less than Q_{hpl} the UD-LTTN system can reduce its total energy utilization when compared to the DHC.

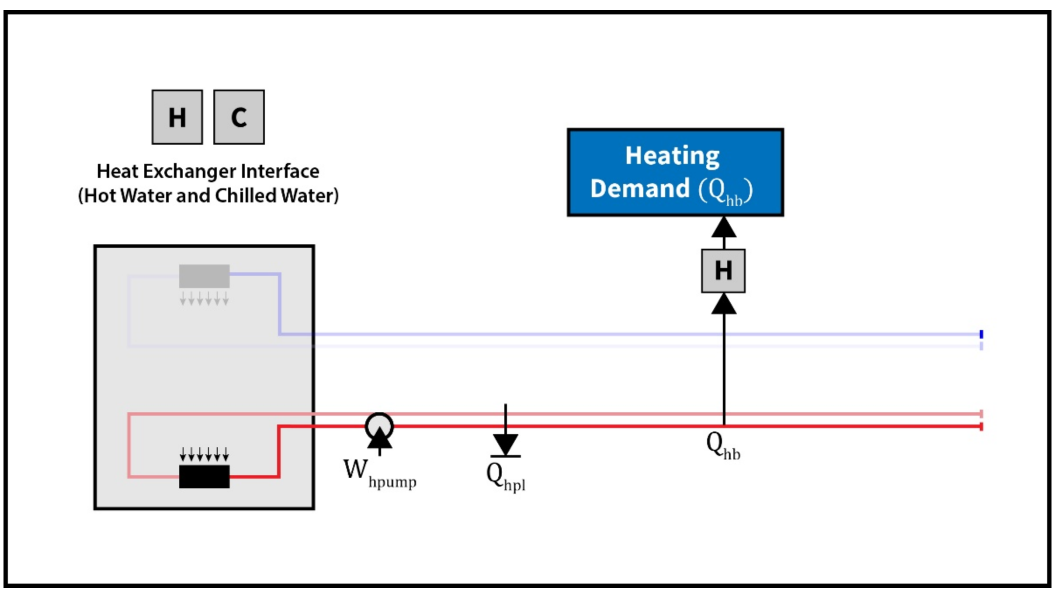

Figure 40 District Heating and Cooling System Energy Balance (Low-Temperature)

Descriptions and a full energy balance included in Equation 6.3

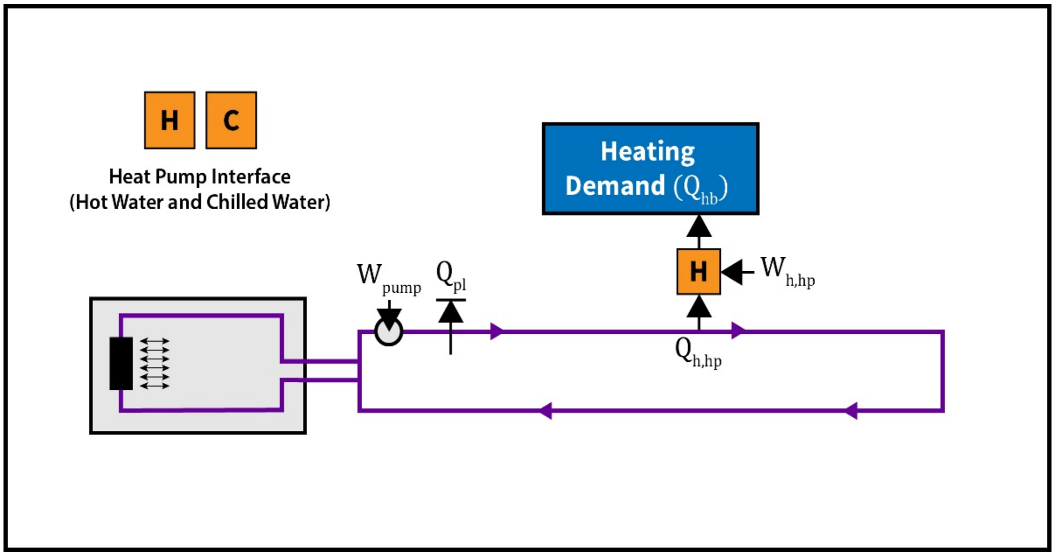

Figure 41 Unidirectional Low Temperature Thermal Network Energy Balance (Low-Temperature)

Descriptions and a full energy balance included in Equation 6.4

$$E = (Q_{hb} + Q_{hpl}) + W_{hpump} \tag{6.3}$$

$$E = (Q_{h,hp} + Q_{pl}) + (W_{pump} + W_{h,hp}) \tag{6.4}$$

Where E is the total energy requirements of the system,
Q_{hb} is the heating demands within a building,
Q_{hpl} is the thermal pipe losses from the heating piping network,
Q_{pl} is the thermal pipe losses from the UD-LTTN piping network,
$Q_{h,hp}$ is the energy transferred to or from the heating heat pump,
$W_{h,hp}$ is the work required by the heating heat pump,
W_{hpump} is the work required by the circulation pump for the heating piping network,
W_{pump} is the work required by the circulation pump for the UD-LTTN piping network,

6.1.3 Excess Waste Energy Concerns

The Comparative Analysis showed that during the Summer period, the UD-LTTN system used 33% more energy than the DHC system. This excess energy requirement is an unexpected externality of a system using two heat pumps in series to reject heat to the atmosphere and is shown for the Summer period in Figure 42 (Equation 6.5).

Since the cooling heat pumps use electrical work to remove energy from the buildings, the amount of energy transferred into the thermal network is equal to the summation of the cooling demands and the electrical work. Normally, when there are simultaneous heating and cooling demands, this additional energy is beneficial and can be used to offset the centralized heating requirements. However, during the Summer period, the community requires predominantly cooling and as such this excess energy must be removed from the thermal network using the centralized air-source chiller located at the Energy Management Centre (EMC).

This absence of energy sharing means that the excess electrical work added to the thermal network by the decentralized heat pump must also be removed by the air-source chiller (Equation 6.7). As a result, this increases the total energy utilization of the system when compared to the DHC system, which does not have to account for the excess work from the heat pump, and the compounded heat pump efficiencies of less than unity. The resulting increase in total energy utilization because of this system configuration is motivation for investigating alternative energy sources that could potentially replace the centralized air-source chiller. These alternatives will be further discussed in Section 6.3.

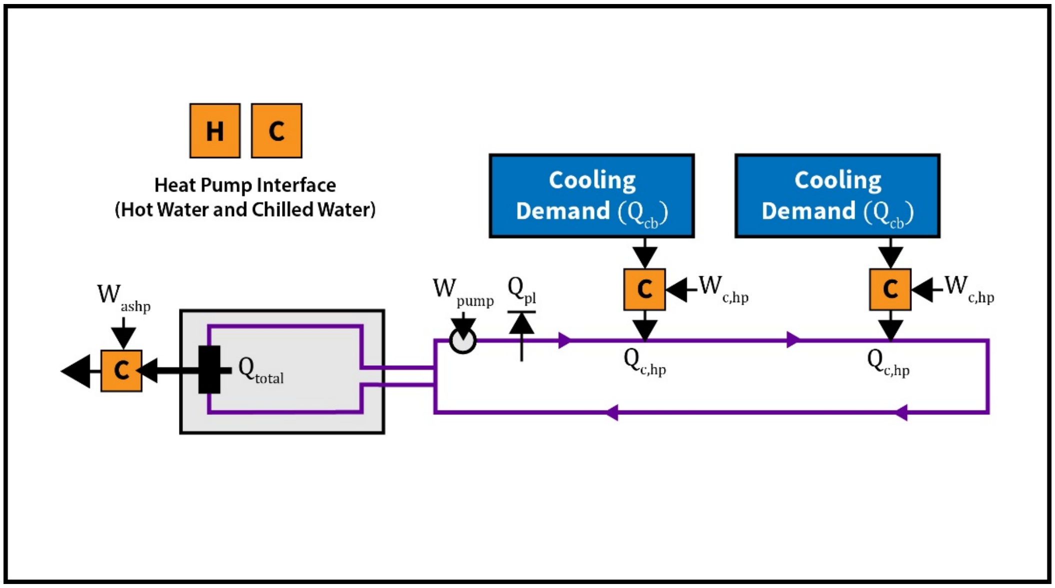

Figure 42 Unidirectional Low Temperature Thermal Network Energy Balance (Excess Waste Energy)

Descriptions and a full energy balance included in Equation 6.5 to Equation 6.7

$$E = W_{c,hp} + W_{ashp} + W_{pump} \tag{6.5}$$

$$Q_{c,hp} = Q_{cb} + W_{c,hp} \tag{6.6}$$

$$E = W_{c,hp} + \frac{(Q_{cb}+W_{c,hp}+Q_{pl})}{COP_{ashp}} + W_{pump} \tag{6.7}$$

$$E = \frac{(Q_{cb}+Q_{pl})}{COP_{ashp}} + W_{pump} \tag{6.8}$$

Where E is the total energy requirements of the system,
Q_{cb} is the cooling demands within a building,
Q_{pl} is the thermal pipe losses from the UD-LTTN piping network,
$Q_{c,hp}$ is the energy transferred to or from the cooling heat pump,
W_{ashp} is the work required by the air source heat pump,
$W_{c,hp}$ is the work required by the cooling heat pump,
W_{pump} is the work required by the circulation pump for the UD-LTTN piping network,
COP_{ashp} is the coefficient of performance of the air-source heat pump.

6.2 Predicting Energy Sharing Potential

From the previous analysis, it is clear that although the Low-Temperature Benefit is important, the Energy Sharing Benefit has a much larger impact on system performance. As per the case study, the energy sharing benefit was responsible for the majority of energy savings during the Winter, Spring and Fall Seasons. Hence, the energy sharing potential of communities is a crucial performance indicator for UD-LTTN success and as such, being able to quantify this potential benefit would streamline UD-LTTN design decisions. Using the supply temperature analysis previously described for the case study, it is possible to develop an analytical solution for an Energy Sharing (ES) indicator that measures the energy sharing potential of a community, where a value of 0.0 would indicate ideal energy sharing, and an increasing value speaks to the detriment of a UD-LTTN system. Equation 6.9 to 6.12 describe this methodology.

$$X = \begin{cases} \sum_{1}^{n} \eta_{Th}\left(X_{h(i)} - X_{c(i)}\right) + \eta_e X_{e(i)}, & X_{h(i)} > X_{c(i)} \\ \sum_{1}^{n} \eta_e X_{e(i)}, & X_{h(i)} = X_{c(i)} \\ \sum_{1}^{n} \eta_{Tc}\left(X_{c(i)} - X_{h(i)}\right) + \eta_e X_{e(i)}, & X_{h(i)} < X_{c(i)} \end{cases} \tag{6.9}$$

Where:

$$X_{c(i)} = \left(Q_{cb(i)} + \frac{Q_{cb(i)}\left(T_s - T_{cs(i)}\right)}{\eta_{cc(i)} T_{cs(i)}}\right) \qquad X_{h(i)} = \left(X_{hb(i)} - \frac{Q_{hb(i)}\left(T_{hs(i)} - T_s\right)}{\eta_{hc(i)} T_{hs(i)}}\right)$$

$$X_{e(i)} = \left[\frac{Q_{hb(i)}\left(T_{hs(i)} - T_s\right)}{\eta_{hc(i)} T_{hs(i)}} + \frac{Q_{cb(i)}\left(T_s - T_{cs(i)}\right)}{\eta_{cc(i)} T_{cs(i)}}\right]$$

$$E_{UD-LTTN} = \begin{cases} \sum_{1}^{n} \left(E_{h(i)} - E_{c(i)}\right) + E_{e(i)}, & E_{h(i)} > E_{c(i)} \\ \sum_{1}^{n} E_{e(i)}, & E_{h(i)} = E_{c(i)} \\ \sum_{1}^{n} \left(E_{c(i)} - E_{h(i)}\right) + E_{e(i)}, & E_{h(i)} < E_{c(i)} \end{cases} \tag{6.10}$$

Where:

$$E_{c(i)} = \left(Q_{cb(i)} + \frac{Q_{cb(i)}\left(T_s - T_{cs(i)}\right)}{\eta_{cc(i)} T_{cs(i)}}\right) \qquad E_{h(i)} = \left(Q_{hb(i)} - \frac{Q_{hb(i)}\left(T_{hs(i)} - T_s\right)}{\eta_{hc(i)} T_{hs(i)}}\right)$$

$$E_{e(i)} = \left[\frac{Q_{hb(i)}\left(T_{hs(i)} - T_s\right)}{\eta_{hc(i)} T_{hs(i)}} + \frac{Q_{cb(i)}\left(T_s - T_{cs(i)}\right)}{\eta_{cc(i)} T_{cs(i)}}\right]$$

$$E_{DHC} = \sum_{1}^{n} Q_{hb(i)} + Q_{cb(i)} \tag{6.11}$$

$$ES = \frac{E_{UD-LTTN}}{E_{DHC}} \tag{6.12}$$

Where ES is the energy sharing indicator,
X is the costing parameter being minimized by the supply temperature optimization,
$E_{UD-LTTN}$ is the total energy demands of the UD-LTTN system,
E_{DHC} is the total energy demands of the DHC system,
$Q_{hb(i)}$ is the heating demands for building [i],
$Q_{cb(i)}$ is the cooling demands for building [i],
$T_{hs(i)}$ is the preferred hot water supply temperature for building [i],
$T_{cs(i)}$ is the preferred cold water supply temperature for building [i],
T_s is the supply temperature of the UD-LTTN,
η_e is the electrical costing parameter,
η_{Th} is the thermal costing parameter for heating generation,
η_{Tc} is the thermal costing parameter for cooling generation,
$\eta_{cc(i)}$ is the Carnot Efficiency for the cooling heat pump at building [i],
$\eta_{hc(i)}$is the Carnot Efficiency for the heating heat pump at building [i],
n is the number of buildings within the community

Similar to the energy balance analysis, this equation sets compares the total energy requirements of a UD-LTTN system against the total energy requirements of a DHC system. Equation 6.10 represents the energy balance for the UD-LTTN system and includes both the energy sharing term and a term for the additional heat pump electrical work. The calculation of these terms first requires optimization of T_s using Equation 6.9 in order to determine the ideal operating conditions for the UD-LTTN system (like in the comparative analysis parameterization). As with the previous supply temperature analysis, different costing factors could be applied to differentiate between the electrical and thermal generation requirements. Once this has been determined, T_s can then be used to calculate $\mathrm{E}_{\mathrm{UD-LTTN}}$ using Equation 6.10, which is the total energy generation requirements of the system. Similarly, Equation 6.11 represents the energy balance for the DHC system by summating the total demands within the community, and finally, Equation 6.12 calculates the ES indicator using the two previously calculated values. For the ES indicator, values closer to 0.0 indicate high levels of energy sharing potential.

Although this measure of energy sharing potential is a valuable relationship for analyzing community behaviour, it is important to recognize the assumptions inherent with this relationship. Unlike the Modelica analysis, Equation 6.10 and 6.11 do not consider the thermal pipe losses and the pumping power requirements within the UD-LTTN and DHC systems, though these were small portions of the total system energy as described in the comparative analysis. Additionally, specifically for the UD-LTTN system, Equation 6.10 does not account for changes in supply temperature when determining the system-wide performance and assumes that all captured thermal energy within the community can be used to offset the community's heating demands, without any considerations for building layout or order. To include this level of detail, more complex analysis is required, however within the broader study of UD-LTTN systems, this relationship allows for high-level analysis of the energy sharing potential of communities.

To determine the impact of these assumptions, the analytical solution shown in Equation 6.9 was used to calculate the total energy requirements of the UD-LTTN system for the case community during the four testing periods. These totals were then compared to the results of the Comparative Analysis (

Table 12). As expected, for each season, the analytical solution under predicts the total energy requirements, and this is mainly because of the omission of the pumping power requirements and the thermal pipe losses. As such, although the analytical solution is not a substitute for component modelling, it is still an effective means to predict a community's energy sharing potential.

Table 12 Total Energy Utilization Comparison – Modelica versus Analytical Solution

	Winter	**Spring**	**Summer**	**Fall**
Modelica	87.0	51.5	49.9	36.6
Analytical	85.3	49.7	47.0	35.1
Relative Error	1.95%	3.50%	5.81%	4.10%

In order to test the Energy Sharing indicator methodology for measuring the sharing potential of communities, some additional testing was done utilizing the historical building loads. Using this data, a virtual community was created with identical heating and cooling demands. A demand intensity gain (G_h) was then applied to the heating data spanning from 0.10 to 10.0 in order to analyze the performance of different load diversities. For example, when G_h is equal to 0.10, the sample community's cooling demands are ten times higher than its heating demands. When Gh is equal to 10.0, the sample community's heating demands are ten times higher than its cooling demands. This demand intensity gain allowed for the assessment of energy sharing potential for a variety of communities with different load diversities.

Using these sample communities, ES indicators were calculated for a large range of community types. Like with the Supply Temperature Optimization, a parameter sweep was performed to determine the optimal temperature of the UD-LTTN network that would maximize each system performances. This parameter sweep was done using the same building supply temperature requirements as in the case study (T_{hs} = 75°C, T_{cs} = 5°C), the same Carnot efficiencies, and was done using 1.0°C steps from 15°C to 25°C. Although primary energy factors could be used to differentiate between electrical and thermal generation requirements, for this analysis, both were weighted as equals ($\eta_{Th}, \eta_{Tc}, \eta_e$ = 1.0). This choice undoubtedly advantages the UD-LTTN system by assuming there is an infinite source of renewable electricity available; however the purpose of this additional analysis is to determine the maximum energy sharing potential of these communities, and as such, this assumption is in line with the overall goal.

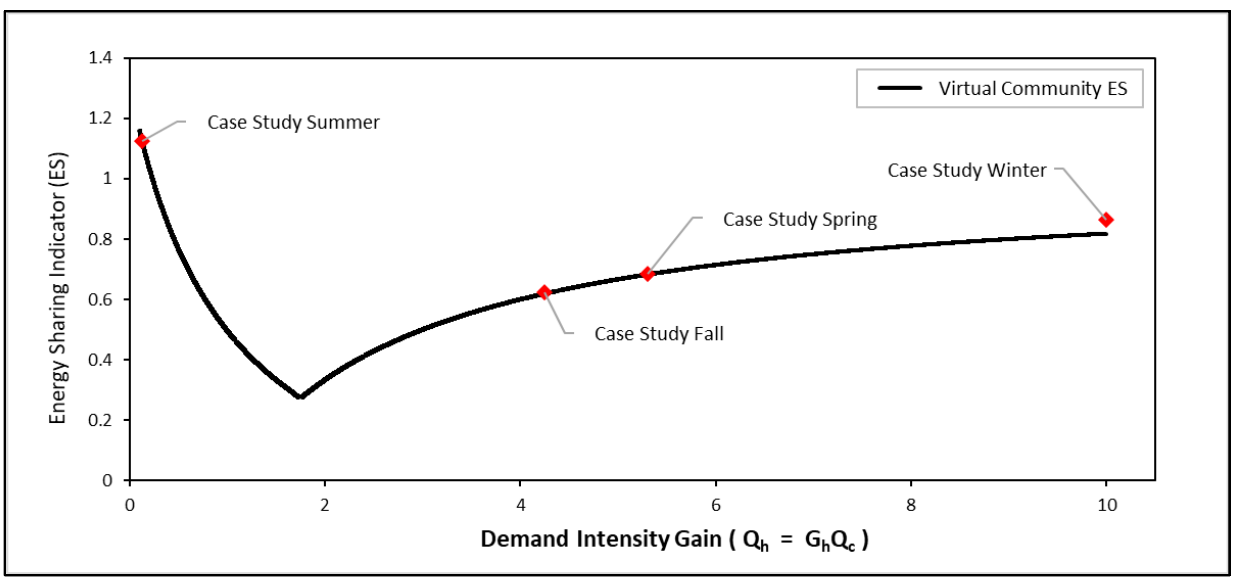

Figure 43 Energy Sharing Potential Comparisions

By using these values, the optimal value of T_S was determined for each community type, and this was used to calculate the optimal total generation requirements of each community using Equation 6.10. Using this optimal value, the ES indicator was calculated and was plotted against the community G_h value for each community type (Figure 43).

From this analysis, it is clear that a high level of energy sharing is possible using UD-LTTN systems with the ES indicator reaching a minimum value of 0.27. This minimum value is equivalent to the UD-LTTN system reducing the community's total energy utilization by 73% when compared to the traditional DHC system and occurs when the community has a heating to cooling ratio of 17:10 (G_h = 1.7). This result is further supported by the findings of the energy balance analysis. Since the energy captured from the decentralized cooling demands is equal to the energy demands within the building plus the electrical work of the heat pump, communities that maximize energy sharing will be communities that are heating demand dominant. After the minimum of 0.27, the energy sharing potential begins to decrease as the system becomes predominantly heating.

It is worth noting that this 73% maximum value for energy sharing is not a theoretical maximum, but a situation-specific maximum based upon the efficiencies of the heat pumps and air chiller simulated. It is also important to remember that building order is ignored in this analysis, and it is assumed there is perfect sharing between TDERs and buildings that require heating. In reality, this is not the case, and only heating demands located downstream of TDERs will be able to take advantage of the energy sharing benefit.

Additional to this more general analysis, the energy sharing potential of the case study used in the Comparative Analysis was also determined for each testing period (Figure 43). From this analysis, it is clear that although the case community had promising results, it inherently has a lower energy sharing potential. Although other case studies with higher ES indicators would yield better results, it is important to remember that this ES indicator measures the energy sharing benefit of simultaneous heating and cooling operations. As such, it may be difficult to find a community that has a heating to cooling ratio of 17:10 throughout the entire year. For example, a residential multiunit residential building in Toronto has 3549 degree heating days and 1188 degree cooling days [75]. This cycle of periodic demands makes it unlikely that the ideal ratio of simultaneous demands is achievable by relying on thermal conditioning demands alone. Therefore, for a UD-LTTN system to achieve higher levels of energy utilization, additional baseload cooling demands must be integrated within the community such as grocery stores or datacentres.

From this analysis, it is clear that demand diversity is a key attribute that governs UD-LTTN system success. Unlike other operational parameters, this attribute is community-dependent. If communities don't have balanced simultaneous heating and cooling demands, additional storage and waste energy sources will be required in order to increase the effectiveness of the UD-LTTN system. If these additional assets are unavailable, the UD-LTTN system will be unable to capitalize on the energy sharing benefit and will likely become less efficient than traditional DHC systems.

6.3 UD-LTTN Energy Generation Sources

From the Comparative Analysis, it became clear that having excess waste energy present in the community can be detrimental to UD-LTTN performance. As such, it is important to consider other types of energy sources, both equipment based and naturally occurring that would improve system performance. This section discusses how potential changes to the UD-LTTN's energy supply, could have affected the performance of the system during the comparative analysis.

Previously with the comparative analysis, all centralized heating demands were provided by a natural gas boiler, and all cooling demands were provided by an air source chiller. However, due to the low-temperature nature of the UD-LTTN system (10°C to 30°C), there are additional energy sources that could be used to meet the centralized generation requirements of the UD-LTTN system. For heating, this includes low grade (LG) waste heat sources (T_S = 30°C) from TDERs within the community and for cooling this includes ambient energy sources ($T_S \leq$ 20°C) such as a geo-exchange system.

Both of these energy sources could dramatically change the performance of the UD-LTTN system during the peak seasons. Therefore to assess their impact on the performance of the system, each of these new energy sources was applied to the Comparative Analysis results during the Winter and Summer seasons.

6.3.1 Winter Season

During the winter season, there was minimal energy sharing, and as such, the UD-LTTN system utilized only 10% less energy than the DHC system. Additionally, during this period, it was determined that the optimal supply temperature should set to approximately 25°C, in order to maximize the efficiency of the decentralized heat pumps. As such, the EMC would need to maintain a supply temperature of 25°C throughout the two week testing period.

This supply temperature is ideal for the integration of low-grade waste energy sources, and if such a source existed near the case community, the centralized heating generation requirements could be completely eliminated. Specifically, this integration of low-grade waste heat would result in the UD-LTTN system utilizing 77% less energy than the DHC system during this period and would effectively eliminate the need for conventional equipment-based generation at the centralized plant (Table 13). This opportunity is yet another benefit of the lower supply temperature of UD-LTTN systems.

Table 13 UD-LTTN Performance with Low-Grade Waste Energy Source

		DHC System			**UD-LTTN System**				
Heating Generation	**Cooling Generation**	*Heating (NG)*	*Cooling (ELEC)*	*Total*	*Heating (NG)*	*Cooling (ELEC)*	*ETS Power (ELEC)*	*Total*	*UD/DHC*
Natural Gas Boiler	*Air-Source Heat Pump*	94.9	1.7	96.6	46.8	0	39.6	87	0.90
Low Grade Waste Heat	*Air-Source Heat Pump*	94.9	1.7	96.6	0	0	21.9	21.9	0.23

6.3.2 Summer Season

During the Summer season, the UD-LTTN system required 33% more energy because of the series nature of the centralized and decentralized heat pumps. This result was an unexpected externality of including decentralized generation. However, the same decentralized heat pumps also enable innovative centralized energy sources by allowing the UD-LTTN system to operate at lower temperatures.

From the temperature analysis it was determined that during the Summer period, the UD-LTTN system should operate with a supply temperature ranging from 15°C to 20°C in order to maximize the efficiency of the decentralized heat pumps. This temperature is ideal for ambient energy sources, and by interfacing with either a geo-exchange system or an ambient source of water, the UD-LTTN system could eliminate its centralized generation requirements during this period.

Specifically, it was found that by introducing an ambient energy source for centralized cooling, the UD-LTTN system would utilize 41% less energy than the DHC system during the Summer period (Table 14). In total, this represents a 74% improvement from the air-source heat pump implementation and is indicative of how detrimental excess waste energy can be to UD-LTTN system performance when proper centralized energy sources are unavailable.

Table 14 UD-LTTN Performance with Ambient Energy Source

		DHC System			**UD-LTTN System**				
Heating Generation	**Cooling Generation**	*Heating (NG)*	*Cooling (ELEC)*	*Total*	*Heating (NG)*	*Cooling (ELEC)*	*ETS Power (ELEC)*	*Total*	*UD/DHC*
Natural Gas Boiler	*Air-Source Heat Pump*	13.2	24.2	37.4	0	27.4	21.9	49.9	1.33
Natural Gas Boiler	*Ambient Energy Source*	13.2	24.2	37.4	0	0	21.9	21.9	0.59

Chapter 7

7. Conclusions and Recommendations

7.1 Conclusions

As communities around the world push for more efficient energy systems, increasing focus is being put on utilizing every Watt of energy created. To accomplish this, communities will have to take advantage of all energy resources, both centralized and decentralized, in an integrated system that increases total energy utilization. This thesis assessed the potential of a Unidirectional Low Temperature Thermal Network (UD-LTTN) to act as this integrated system. At the onset, a literature review was done to determine the current state of the art. Then a modelling library was developed and checked both numerically and experimentally. Finally, this modelling library was used to compare the performance of UD-LTTN to a traditional District Heating and Cooling (DHC) system and assess the impact of Thermal Distributed Energy Resource (TDER) integration.

7.2 Impact of Distributed Thermal Energy Resources

The main motivation behind this body of work was to investigate the UD-LTTN system's ability to capture thermal energy from TDERs. In the comparative analysis, the UD-LTTN incorporated decentralized cooling demands as a source of waste energy. This decentralized energy recovery increased the performance of the system during the Winter, Spring and Fall seasons by up to 29%.

From a carbon emissions perspective, the UD-LTTN was able to use the additional energy captured from TDERs to reduce the requirements of the centralized boiler. This, in turn, reduces the carbon emissions of the system by on average 70% for the 100% renewable generation case, with decreasing reductions occurring as the electrical supply becomes less than 50% renewable.

The comparative analysis also showed that both the supply temperature and the mass flow rate of a UD-LTTN system are important parameters for system success. For each of these parameters, additional analysis was performed to determine the ideal set-points for the chosen case study. From this analysis it was found that while the mass flow rate is an important parameter for system stability, the supply temperature is an important parameter for system effectiveness and can a dramatic effect on system-wide energy utilization. This is because the optimal supply temperature is dependent on the demand diversity of the community, and as such, must change dynamically as the community's demand requirements fluctuate from being heating dominate to cooling dominate.

Beyond the comparative analysis, additional work was conducted during the thematic analysis to extend the findings from the case study to the general field of UD-LTTN design. Specifically, this analysis focused on the creation of a methodology that could predict the energy sharing potential of different communities. This methodology was then used to assess the sharing potential for a variety of different communities with varying levels of TDER integration.

From this assessment, it was determined that although the comparative analysis showed promising results, other communities with higher densities of TDERs could achieve far higher levels of energy sharing. Specifically, it was found that for the given operational parameters, communities with heating to cooling ratios equal to 17:10 could potentially reduce the total energy utilization of the community by up to 72% when compared to traditional DHC systems.

However, this high level of energy sharing was only possible under ideal conditions when it was assumed that the system's thermal pipe losses are non-existent and that community shares 100% of energy captured from TDERs. In reality, these conditions are hard to achieve; however, through further research innovation and improvements to UD-LTTN system design, they may be achievable in the future. With this in mind, this last section provides some recommendations for future work that could further increase the efficiency of Unidirectional Low Temperature Thermal Networks with Thermal Distributed Energy Resource integration.

7.3 Recommendations for Future Work

7.3.1 Decentralized Storage

Decentralized storage could have an important role to play in UD-LTTN systems. By including behind the heat pump storage at each building, it would be possible to store excess waste energy within the building for later use (Figure 44). This maneuver would be especially beneficial during the Spring and Fall seasons when there is a daily switch over between the cooling and heating demands in each building. As with all storage solutions, additional research is required to determine the size of the storage tank and the temperature differences between the supply and return connections. Since the tank is behind the heat pump, the temperature drop across the tank is constrained by the maximum outlet temperature of the heat pump. In cases such as a retrofit application, the heat pump may not be able to increase its outlet temperature above the temperature setpoint required by the building HVAC system. This constraint would require the storage tank to store energy at the HVAC's preferred temperature, resulting in a massive stratified storage tank, akin those used in other DHC systems. In support of this work, the UD-LTTN Modelica library was expanded to support storage integration with a summary of these additional models included in Appendix D.

Although this decentralized storage solution could potentially increase the performance of the UD-LTTN system during the Spring and Fall seasons, it is unlikely to improve the UD-LTTN system's performance during the Summer season. This is because while decentralized storage is a short-term solution that can potentially eliminate the rejection of thermal energy during periods of mixed demands. However, during the summer, the demands are predominantly cooling, and as such an additional long term solution will be required to address this seasonal imbalance.

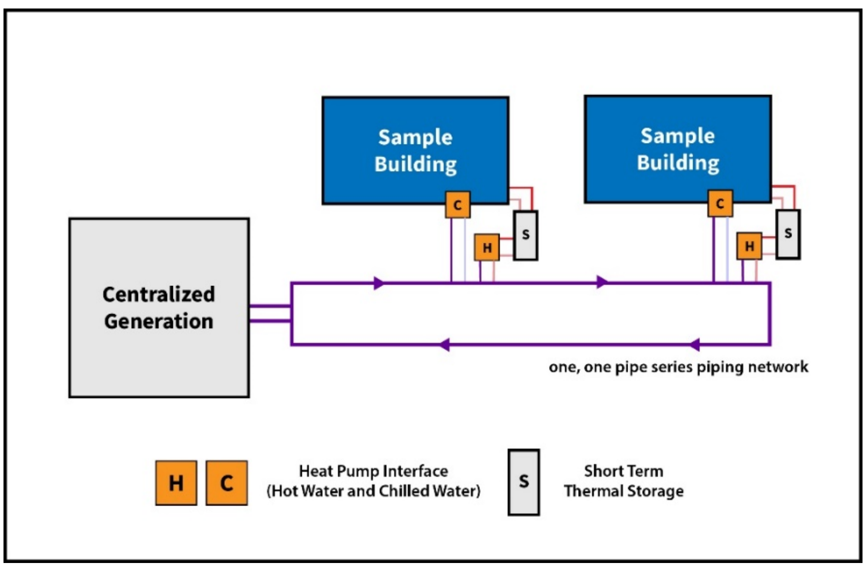

Figure 44 UD-LTTN System with Decentralized Thermal Storage

7.3.2 Seasonal Storage

Like with decentralized storage, seasonal storage also has the potential to increase UD-LTTN system performance. As was described in the thematic analysis, if a community has the appropriate ratio of simultaneous heating and cooling demands, the energy sharing benefit has can potentially reduce total energy utilization by up to 73%. However, due to the seasonal nature of thermal conditioning, it is unlikely that this ideal ratio of heating and cooling demands is possible without relying on buildings that have baseload cooling demands (datacentres, or grocery stores). This imbalance in seasonal demand is ideal for seasonal storage, as it can capture excess waste energy during the summer season and then use this energy to provide heating during the winter season. In this way, the community can still use the waste energy generated from cooling operations as a thermal generation source. Additional work is required to assess the potential of different seasonal storage technologies, and determine which systems are best suited for UD-LTTN system integration.

7.3.3 Ambient Energy Sources for Cooling

Since the UD-LTTN system operates at lower supply temperatures (15°C to 20°C) during the summer, there is the potential to integrate ambient thermal sources to regulate the temperature of the piping network. These sources could include large bodies of water or geo-exchange systems located either at the EMC or throughout the community. In both cases, this energy exchange can occur directly, without the need for additional heat pumps operations. In this way, the UD-LTTN could eliminate the need for centralized cooling operations, and this would greatly increase system-wide performance during the Summer season. For comparison, by eliminating the centralized cooling generation requirements for the Ontario case study during the Summer season, the UD-LTTN system would become 41% more efficient than the DHC system. This result is in stark contrast to the system being initially 33% more energy-intensive due to compounded heat pump efficiencies within the system and is indicative of the potential of ambient energy sources.

7.3.4 Centralized or Decentralized Rejection

The last design option for the management of excess waste energy is using additional electrical energy to reject the waste heat to the environment. From an energy utilization perspective, this option is the least efficient as it involves both the rejection of the captured waste energy and the consumption of additional electrical. For this study's comparative analysis, the system utilized centralized rejection at the EMC to reject the excess waste heat. However, it is recommended that additional work is done to understand the potential benefits of decentralized rejection. Although direct rejection to the ambient air is not possible with the supply temperature of the thermal network (15°C to 20°C), the decentralized heat pumps could increase their output temperature and reject energy directly to the environment through the integration of air source heat exchangers. In this way, the ETS can reject energy directly into the environment, which could potentially reduce the total energy generation requirements of the system.

7.3.5 Pipe Specifications

Pipe design specifications have proven to be an important aspect of 5GDHC design, one that is directly related to both thermal pipe losses and pumping power. Based on the analysis regarding the mass flow rates of UD-LTTN, although high mass flow rates improve system-wide stability, they also increase the pumping power requirements of the system.

Numerous design alterations could be implemented to decrease these additional energy requirements. These include increasing the district pipe diameter, reducing the mass flow rate to allow larger fluctuations of T_S or reducing the size of the series piping network.

With this in mind, an additional analysis was performed using the cooling pipe design specification for the UD-LTTN system. This design change changed the pipe from 125 mm nominal diameter steel pipe to 200 mm nominal diameter D11 HPDE pipe, an approximate 35 mm increase in diameter. For the UD-LTTN this marginal increase greatly reduced the pumping power requirements of the system resulting in a 67% decrease over the heating pipe implementation. With this result in mind, two recommendations are being put forward.

The first recommendation is to choose piping specifications that reduce both pumping power requirements and thermal pipe losses. In general, this would mean giving preference to larger diameter insulated pipes, however additional considerations should be given to the capital costs of such investments. In practice, pipe design specifications should be chosen so that they balance the excess operational costs of pumping with the decreased operational costs associated with reduced thermal pipe losses. This practice may result in higher rates of adoption of HDPE pipes for 5GDHC systems. However, the exact design specification will depend on the layout and size of the community.

The second is to dynamically change the mass flow rate of the system throughout the year in order to reduce the overall pumping power requirements. This fluctuating mass flow rate would still be high during the peak seasons; however, during the shoulder seasons, the mass flow rate could be lowered, allowing the system to decrease its overall electrical consumption.

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Appendix A: Modelica Model Unit Tests

The below section outlines the results for the unit tests performed in order to validate the models. For each model, two tables are presented. The first table outlines the tests performed as well as their purpose, type (TC for a trivial case, A for analytical) and the expected result. The second table indicates the results of each test as well as any additional comments worth noting.

District Pipe

Input Variables:

Pipe Mass Flow ($\dot{m}$), Pipe Supply Temperature (T_s), and various pipe design parameters

Output Variables:

Pipe Thermal Losses (q_{pl}), Pipe Pressure Losses (Δp), Pipe Return Temperature (T_r)

Table 15 District Pipe Model: Unit Tests

Unit Test	Purpose	Type	Procedure	Expected Result
Test 1	T_r	TC	Set $q_{pl} = 0$, measure T_r	$T_r = T_s$
Test 2	T_r	A	Set q_{pl} = const, measure T_r	$T_r = {-q_{pl}}/{\dot{m}C_p} + T_s$
Test 3	Δp	A	Set $\dot{m}$ and pipe parameters, measure Δp	Δp = Analytical Δp
Test 4	Δp	TC	Set $\dot{m} = 0$, measure Δp	$\Delta p = 0$
Test 5	q_{pl}	A	Set pipe design parameters, replicate district heating conditions, measure q_{pl}	q_{pl} = Analytical q_{pl}

Where C_p is the specific heat of the water

Table 16 District Pipe Model: Unit Tests Results

Unit Test	Purpose	Type	Results	Comments
Test 1	T_r	TC	**Passed**	-
Test 2	T_r	A	**Passed**	-
Test 3	Δp	A	**Passed**	Passed when compared to analytical hand calculations. Although some calculations resulted in small errors (< 1.0%), these errors resulted from differing friction factor interpolations [76].
Test 4	Δp	TC	**Passed**	-
Test 5	q_{pl}	A	**Passed**	Results shown in Figure 45 indicate that District Pipe replicates the results predicted by Wallentén [67]. The consistent absolute error is from the District Pipe model measuring T_s at the centre of the first fluid control volume rather than the start of the pipe. The rest of the heat transfer parameters are identical, and in turn, the total heat losses are identical.

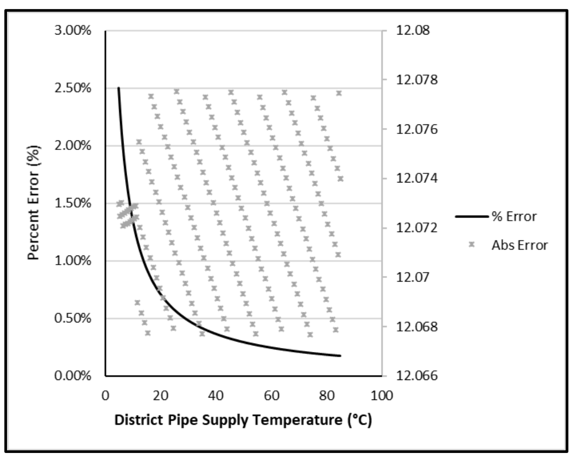

Figure 45 District Pipe Test 5 Results

DHC EMC

Input Variables:

DHC Total Mass Flow ($\dot{m}$) [variable set by control network], DHC Temperature Supply (T_s), DHC Temperature Return (T_r), various peak period parameters,

Output Variables:

EMC Generation Requirements (q_{emc}), EMC Power Requirements (W), EMC Carbon Emissions ($Q_{CO}{}^2$)

Table 17 DHC EMC: Unit Tests

Unit Test	Purpose	Type	Procedure	Expected Result
Test 1	q_{emc}	TC	Set $T_s = T_r$, measure q_{emc}	$q_{emc} = 0$
Test 2	q_{emc}	TC	Set $\dot{m} = 0$, measure q_{emc}	$q_{emc} = 0$
Test 3	q_{emc}	AC	Set $T_s > T_r$, check q_{emc} energy balance	$q_{emc} = \dot{m}C_p(T_s - T_r)$
Test 4	q_{emc}, W	TC	Set peak period parameters, check energy allocations	q_{emc} and W loads to be classified correctly
Test 5	q_{emc}, $Q_{CO}{}^2$	AC	Check that the boiler model calculates $Q_{CO}{}^2$ properly	q_{emc}, $Q_{CO}{}^2$ should equal the analytical results
Test 6	q_{emc}, W,	AC	Check that the simple chiller model calculates W properly	q_{emc}, W should equal the analytical results

Where C_p is the specific heat of the water

Table 18 DHC EMC: Unit Tests Results

Unit Test	Purpose	Type	Results	Comments
Test 1	q_{emc}	TC	**Passed**	-
Test 2	q_{emc}	TC	**Passed**	-
Test 3	q_{emc}	AC	**Passed**	Over a range of mass flow rates and temperatures, the average error was found to be 0.032%. This is likely due to differences in how C_p is evaluated.
Test 4	q_{emc}, W	TC	**Passed**	-
Test 5	q_{emc}, $Q_{CO}{}^2$	AC	**Passed**	This test was successful, and since the same replaceable model is used in the UD-LTTN EMC, it does not need to be repeated.
Test 6	q_{emc}, W	AC	**Passed**	This test was successful, and since the same replaceable model is used in the UD-LTTN EMC, it does not need to be repeated.

DHC ETS

Input Variables:

Building Energy Demand (q), ETS Temperature Supply (T_s), ETS Heat Exchanger Preferred Temperature Difference (ΔT), ETS Heat Exchanger Efficiency (η)

Output Variables:

ETS Temperature Return (T_r), ETS Mass Flow ($\dot{m}$)

Table 19 DHC ETS: Unit Tests

Unit Test	Purpose	Type	Procedure	Expected Result
Test 1	$\dot{m}$	TC	Set q = 0, measure $\dot{m}$	$\dot{m} = 0$
Test 2	T_r	TC	Set q = const, measure T_r	$T_r = T_s - \Delta T$
Test 3	$\dot{m}$	AC	Set q = const, measure $\dot{m}$	$\dot{m} = \frac{q}{\eta C_p (T_s - T_r)}$

Where C_p is the specific heat of the water

Table 20 DHC ETS: Unit Tests Results

Unit Test	Purpose	Type	Results	Comments
Test 1	$\dot{m}$	TC	**Passed**	-
Test 2	T_r	TC	**Passed**	-
Test 3	$\dot{m}$	AC	**Passed**	Overall a series of building demands were simulated and compared against the analytical results. On average, the relative error was found to be 0.048%, and this likely due to differences in how C_p is evaluated.

UD-LTTN EMC

Input Variables:

UD-LTTN Mass Flow Supply ($\dot{m}$) [parameter set by researcher], UD-LTTN Temperature Supply (T_s), DHC Temperature Return (T_r), various peak period parameters,

Output Variables:

EMC Generation Requirements (q_{emc}), EMC Power Requirements (W), EMC Carbon Emissions (Q_{CO^2})

Table 21 UD-LTTN EMC: Unit Tests

Unit Test	Purpose	Type	Procedure	Expected Result
Test 1	q_{emc}	TC	Set $T_s = T_r$, measure q_{emc}	$q_{emc} = 0$
Test 2	q_{emc}	TC	Set $\dot{m} = 0$, measure q_{emc}	$q_{emc} = 0$
Test 3	q_{emc}	AC	Set $T_s > T_r$, check q_{emc} energy balance	$q_{emc} = \dot{m}C_p(T_s - T_r)$
Test 4	q_{emc}, W	TC	Set peak period parameters, check energy allocations	q_{emc} and W loads are classified correctly

Where C_p is the specific heat of the water

Table 22 UD-LTTN EMC: Unit Tests Results

Unit Test	Purpose	Type	Results	Comments
Test 1	q_{emc}	TC	**Passed**	-
Test 2	q_{emc}	TC	**Passed**	Although q_{emc} was equal to zero, since $\dot{m}$ is a parameter set by the researcher it would never be set to zero when simulating UD-LTTNs. In the future, it may be good practice to make $\dot{m}$ a variable that changes with demand according to the derivation in Appendix B
Test 3	q_{emc}	AC	**Passed**	Over a range of mass flow rates and temperatures, the average error was found to be 0.048%. This is likely due to differences in how C_p is evaluated.
Test 4	q_{emc}, W	TC	**Passed**	-

UD-LTTN ETS

For the UD-LTTN ETS, both the ETSH and ETSC models were tested. Both are identical except for that in the ETSC model a different heat pump datasheet is used

Input Variables:

Building Energy Demand (q), ETS Temperature Supply (T_s), ETS Heat Pump Preferred Temperature Difference (ΔT), Building Required Temperature (T_{req})

Output Variables:

ETS Temperature Return (T_r), ETS Mass Flow ($\dot{m}$), ETS Power Requirements (W), ETS COP

Table 23 UD-LTTN ETS: Unit Tests

Unit Test	Purpose	Type	Procedure	Expected Result
Test 1	$\dot{m}$	TC	Set q = 0, measure $\dot{m}$	$\dot{m} = 0$
Test 2	T_r	TC	Set q = const, measure T_r	$T_r = T_s - \Delta T$
Test 3	$\dot{m}$	AC	Set q = const, measure $\dot{m}$	$\dot{m} = \frac{q}{C_p(T_s - T_r)}$
Test 4	COP	AC	Fluctuate T_s and assess the change in COP. Should be within the limits of equipment used within the literature.	Compare against COPs from an equipment database

Where C_p is the specific heat of the water

Table 24 UD-LTTN ETS: Unit Tests Results

Unit Test	Purpose	Type	Results	Comments
Test 1	$\dot{m}$	TC	**Passed**	Although $\dot{m}$ should be equal to zero, for both the ETSH and the ETSC models, the flowrate at q = 0 is equal to 0.001 ml/s. This is because the heat pump model used does not have a control sequence that allows for proper initialization from a zero-mass flow set points. When attempting to start from a zero mass flow setpoint, at the initial time step the mass flow will be very small (10e-15), and the energy flow will be far too large, and this results in very large temperature difference across the heat pump which in turn results in an error. To avoid this, 0.001 ml/s has been allowed to pass through the heat pump when q is equal to zero. As a result, this leads to a maximum error of 0.01 W of energy being transferred instead of the assumed zero. Since most buildings often have baseload energy requirements greater

				than zero and community demand requirements are many orders magnitudes higher than this error, this strategy was deemed acceptable.
Test 2	T_r	TC	**Passed**	-
Test 3	$\dot{m}$	AC	**Passed**	-
Test 4	COP	AC	**Passed**	For both the ETSC and the ETSH models, T_s was increased from 15°C to 25°C. This was the average supply range of the equipment datasheets that were used to determine the Carnot Efficiency of the models. For this datasheet database, the heating COPs ranged from 2.42 to 3.56, and the cooling COPs ranged from 4.00 to 7.03. The resulting COPs of the ETSC and ETSH models are displayed in Figure 46 and Figure 47. For the ETSC model, it was found that the model's COP was less efficient than the average of the Datasheet Database. However, it did more closely relate to a few of the sampled reversible heat pumps. On the other hand, the ETSH model exhibited similar results to the average Datasheet Database COP and turned out to be only slightly less efficient.

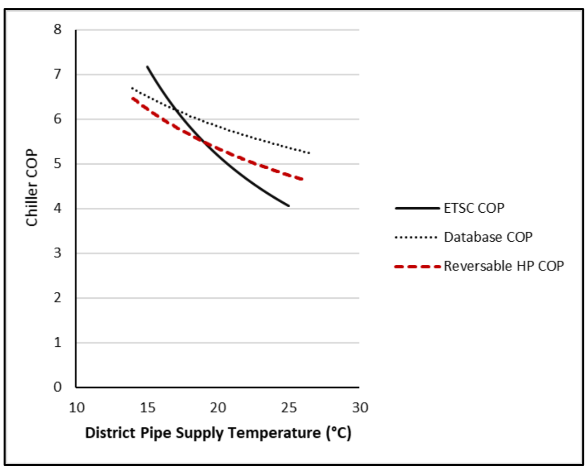

Figure 46 ETSC Test 4 Results

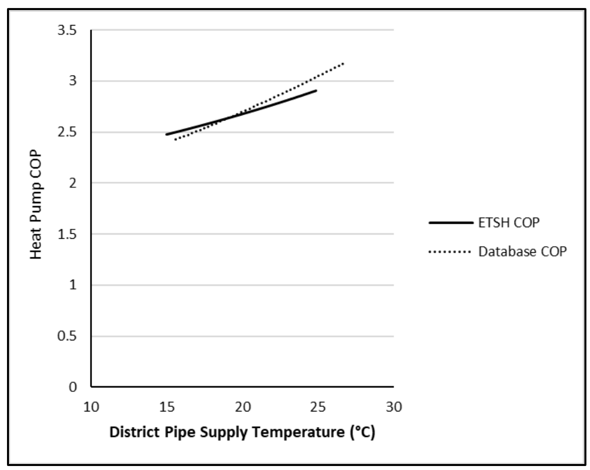

Figure 47 ETSH Test 4 Results

Appendix B: UD-LTTN Supply Temperature Derivation

The supply temperature of a Unidirectional system is an important parameter for effectively utilizing the UD-LTTN's electrical and thermal generation resources. In order to understand this implication, one must first consider the general energy balance for a singular building ETS within a UD-LTTN system (A.1)

$$Total\ ETS\ Energy: \quad U = \Delta Q + W \qquad [A.1]$$

Where ΔQ represents the difference between the total amount of thermal energy transferred from the loop (Q_{hl}) and the total amount of thermal energy transferred into the loop (Q_{cl}) [A.2].

$$\Delta Q = |Q_{hl} - Q_{cl}| \qquad [A.2]$$

This absolute difference is used to idealize the sharing processes within the UD-LTTN. It assumes that one hundred percent of waste heat recovered from the ETS's cooling process can be used to provide for the ETS's heating demands. Expanding this approach to multiple buildings within the system leads to the derivation of equation [A.3].

$$\Delta Q_{ULTTN} = \sum_{1}^{n} \left| Q_{hl(i)} - Q_{cl(i)} \right| \qquad [A.3]$$

However, thermal demands are generally not described as energy flows to and from the loop. Instead, they are described by the energy demands at the building level (Q_{hb} and Q_{cb}). By using [A.4], these values are substituted into equation [A.3] creating [A.5].

$$COP = \frac{Q_b}{Q_b - Q_l} \qquad [A.4]$$

$$\Delta Q_{ULTTN} = \sum_{1}^{n} \left| \left(Q_{hb(i)} - \frac{Q_{hb(i)}}{COP_{h(i)}} \right) - \left(Q_{cb(i)} + \frac{Q_{cb(i)}}{COP_{c(i)}} \right) \right| \qquad [A.5]$$

Where COP can be calculated using equations [A.6] and [A.7].

$$COP_h = \frac{\eta_h T_{hs}}{T_{hs} - T_s} \quad [A.6] \qquad COP_c = \frac{\eta_c T_{cs}}{T_s - T_{cs}} \quad [A.7]$$

Now that an expression for ΔQ has been derived, a similar equation can be derived for W. The total electrical energy of the system is equal to the summation of all heat pump loads, both for cooling and heating [A.8]. Using equation [A.4], we can describe the total electrical work as a function of building demands and COPs [A.9].

$$W_{ULTTN} = \sum_{1}^{n} W_{h(i)} + W_{c(i)} \qquad [A.8]$$

$$W_{ULTTN} = \sum_{1}^{n} \frac{Q_{hb(i)}}{COP_{h(i)}} + \frac{Q_{cb(i)}}{COP_{c(i)}} \qquad [A.9]$$

Combining [A.5] and [A.9], we then get the total energy utilization of the community [A.10]. It is now possible to remove the energy association of this derivation by incorporating the costing parameters η_e and η_T [A.10]. These parameters allow for Ts to be optimized with respect to any costing constraint.

$$U_{ULTTN} = \sum_{1}^{n} \left| \left(Q_{hb(i)} - \frac{Q_{hb(i)}}{COP_{h(i)}} \right) - \left(Q_{cb(i)} + \frac{Q_{cb(i)}}{COP_{c(i)}} \right) \right| + \frac{Q_{hb(i)}}{COP_{h(i)}} + \frac{Q_{cb(i)}}{COP_{c(i)}} \qquad [A.9]$$

$$X = \sum_{1}^{n} \eta_T * \left| \left(Q_{hb(i)} - \frac{Q_{hb(i)}}{COP_{h(i)}} \right) - \left(Q_{cb(i)} + \frac{Q_{cb(i)}}{COP_{c(i)}} \right) \right| + \eta_e * \left[\frac{Q_{hb(i)}}{COP_{h(i)}} + \frac{Q_{cb(i)}}{COP_{c(i)}} \right] \qquad [A.10]$$

Substituting in equation [A.6] and [A.7], we can express this equation with regards to T_s.

$$X = \sum_{1}^{n} \eta_T * \left| \left(Q_{hb(i)} - \frac{Q_{hb(i)}\left(T_{hs(i)} - T_s\right)}{\eta_{hc(i)} T_{hs(i)}} \right) - \left(Q_{cb(i)} + \frac{Q_{cb(i)}\left(T_s - T_{cs(i)}\right)}{\eta_{cc(i)} T_{cs(i)}} \right) \right|$$

$$+ \eta_e * \left[\frac{Q_{hb(i)}\left(T_{hs(i)} - T_s\right)}{\eta_{hc(i)} T_{hs(i)}} + \frac{Q_{cb(i)}\left(T_s - T_{cs(i)}\right)}{\eta_{cc(i)} T_{cs(i)}} \right] \qquad [A.11]$$

Where $Q_{hb(i)}$ is the heating demands for building [i],
$Q_{cb(i)}$ is the cooling demands for building [i],
$T_{hs(i)}$ is the preferred hot water supply temperature for building [i],
$T_{cs(i)}$ is the preferred chilled water supply temperature for building [i],
T_s is the supply temperature of the UD-LTTN,
η_T is the thermal costing parameter,
η_e is the electrical costing parameter.
$\eta_{cc(i)}$ is the Carnot Efficiency for the cooling heat pump at building [i],
$\eta_{hc(i)}$ is the Carnot Efficiency for the heating heat pump at building [i],
n is the number of buildings within the community

For equation [A.11], η_e and η_T are dynamic calculations and change depending on the instantaneous community demands. This dependency is especially true for η_T, which must switch between being both a heating and cooling costing parameters (η_{Tc} and η_{Th}) depending on the dominant demands within the system. To better describe this seasonal switchover, Equation [A.11] can be rewritten as a piecewise function that is dependent on the dominant space conditioning operation [A.12].

$$X = \begin{cases} \sum_{1}^{n} \eta_{Th}\left(X_{h(i)} - X_{c(i)}\right) + \eta_e X_{e(i)}, & X_{h(i)} > X_{c(i)} \\ \sum_{1}^{n} \eta_e X_{e(i)}, & X_{h(i)} = X_{c(i)} \\ \sum_{1}^{n} \eta_{Tc}\left(X_{c(i)} - X_{h(i)}\right) + \eta_e X_{e(i)}, & X_{h(i)} < X_{c(i)} \end{cases} \quad \text{[A.12]}$$

Where:

$$X_{c(i)} = \left(Q_{cb(i)} + \frac{Q_{cb(i)}\left(T_s - T_{cs(i)}\right)}{\eta_{cc(i)} T_{cs(i)}}\right) \qquad X_{h(i)} = \left(X_{hb(i)} - \frac{Q_{hb(i)}\left(T_{hs(i)} - T_s\right)}{\eta_{hc(i)} T_{hs(i)}}\right)$$

$$X_{e(i)} = \left[\frac{Q_{hb(i)}\left(T_{hs(i)} - T_s\right)}{\eta_{hc(i)} T_{hs(i)}} + \frac{Q_{cb(i)}\left(T_s - T_{cs(i)}\right)}{\eta_{cc(i)} T_{cs(i)}}\right]$$

Where X is the costing parameter being minimized
$Q_{hb(i)}$ is the heating demands for building [i],
$Q_{cb(i)}$ is the cooling demands for building [i],
$T_{hs(i)}$ is the preferred hot water supply temperature for building [i],
$T_{cs(i)}$ is the preferred cold water supply temperature for building [i],
T_s is the supply temperature of the UD-LTTN,
η_e is the electrical costing parameter,
η_{Th} is the thermal costing parameter for heating generation,
η_{Tc} is the thermal costing parameter for cooling generation,
$\eta_{cc(i)}$ is the Carnot Efficiency for the cooling heat pump at building [i],
$\eta_{hc(i)}$is the Carnot Efficiency for the heating heat pump at building [i],
n is the number of buildings within the community

Equation [A.11] can be simplified by using total energy values for the community rather than doing an individual building summation [A.13]. In this simplified form, it is assumed that all buildings have the same temperature requirements (T_h and T_c) which makes COP_h and COP_c constants, regardless of building type. The simplified form also assumes that all energy captured from decentralized cooling within the community is used to cover system-wide heating demands. In this way, the simplified form does not account for building order when considering energy sharing.

$$X = \eta_T * \left|\left(Q_h - \frac{Q_h(T_{hs} - T_s)}{\eta_h T_{hs}}\right) - \left(Q_c + \frac{Q_c(T_s - T_{cs})}{\eta_c T_{cs}}\right)\right| + \eta_e * \left[\frac{Q_h(T_{hs} - T_s)}{\eta_h T_{hs}} + \frac{Q_c(T_s - T_{cs})}{\eta_c T_{cs}}\right] \quad [A.13]$$

Appendix C: Series UD-LTTN Mass Flow Derivation

To determine the $\dot{m}$ so that T_s is stable, five equations must be developed. The first equation [B.1] calculates $\dot{m}$, while the other four are used to determine which value of Q_{max} should be used in the calculation.

$$\dot{m} = \frac{Q_{max}}{C_p \Delta T_{max}} \quad [B.1]$$

Where $\dot{m}$ is the minimum mass flow rate with the UD-LTTN,
ΔT_{max} is the maximum allowable change in T_s,
C_p is the specific heat capacity of water,
Q_{max} is the maximum energy transfer to or from the UD-LTTN,

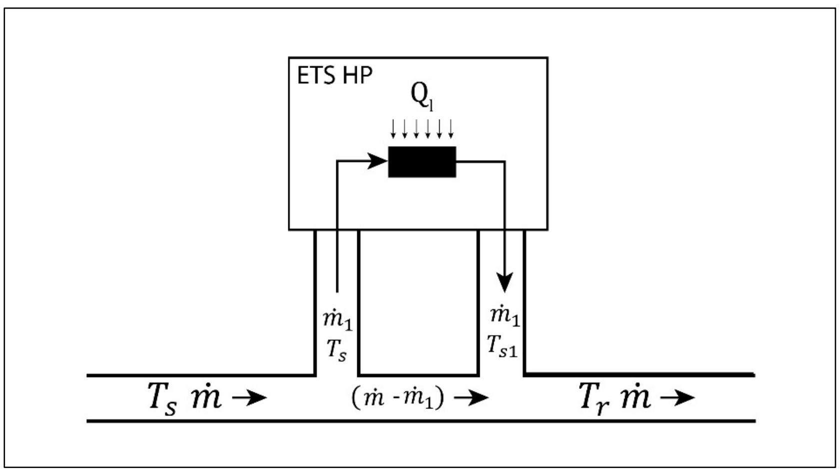

Figure 48: UD-LTTN ETS Energy Balance

To derive equation [B.1], one should consider the energy balance within the supply pipe at the building ETS [B.2] (Figure 48). At this point, the ETS transfers energy (Q_l) either into our out of the pipe, which will change the temperature in the pipe by some value ΔT depending on the mass flow rate of the pipe ($\dot{m}$) and the specific heat capacity (C_p). Rearranging this equation to solve $\dot{m}$, and substituting in ΔT_{max} and Q_{max} leads to equation [B.1]

$$Q_l = \dot{m}C_p(T_s - T_r) \qquad [B.2]$$

Next, the derivations of the three measures of Q_{max} will be explained starting with $Q_{\max(h)}$ and $Q_{\max(c)}$. These measurements consider both individual and consecutive building loads. At a high level, this can be summarized by equations [B.3] and [B.4]. These equations summarize the summation of Q_l values for both heating and cooling buildings occurring consecutively.

$$Q_{\max(h)} = Q_{hl(1)} + Q_{hl(2)} + Q_{hl(3)} \dots \; or \;\; Q_{\max(h)} = \sum_{1}^{k} Q_{hl(i)} \qquad [B.3]$$

$$Q_{\max(c)} = Q_{cl(1)} + Q_{cl(2)} + Q_{cl(3)} \dots \; or \;\; Q_{\max(c)} = \sum_{1}^{j} Q_{cl(i)} \qquad [B.4]$$

Where both k and j represent the number of consecutive heating and cooling buildings, respectively. When either k or j are equal to zero, the summation calculates the energy transfer rate for one building, which in some cases could be Q_{max}. Since it is often more practical to describe energy transfers to and from the loop in term of building energy demands, some substitutions are made. Using equations [B.5], Q_l can be expressed in terms of the current building demands (Q_b) and the coefficient of performance of the individual building heat pumps (COP_h for heating, and COP_c for cooling) [B.6][B.7].

$$COP = \frac{Q_b}{Q_b - Q_l} \qquad [B.5]$$

$$Q_{\max(h)} = \sum_{1}^{k} Q_{hb(i)} - \frac{Q_{hb(i)}}{COP_{h(i)}} \qquad [B.6] \qquad\qquad Q_{\max(c)} = \sum_{1}^{j} Q_{cb(i)} - \frac{Q_{cb(i)}}{COP_{c(i)}} \qquad [B.7]$$

Expressions [B.6] and [B.7] are ideal for calculating $Q_{\max(h)}$ and $Q_{\max(c)}$ in experimental facilities where the COPs of the heat pumps are known. However, for system design, it is helpful to be able to equate these values using Carnot cycles. Using equation [B.8] and [B.9], COP_h and COP_c can be expressed in terms of the systems relevant temperatures and a Carnot efficiency. This, in turn, leads to the final derivations for $Q_{\max(h)}$ and $Q_{\max(c)}$, equations [B.10] and [B.11].

$$COP_h = \frac{\eta_{hc} T_{hs}}{T_{hs} - T_s} \quad [B.8] \qquad COP_c = \frac{\eta_{cc} T_{cs}}{T_s - T_{cs}} \quad [B.9]$$

$$Q_{\max(h)} = \sum_{1}^{k} Q_{hb(i)} - \frac{Q_{hb(i)}\left(T_{hs(i)} - T_s\right)}{\eta_{hc(i)} T_{hs(i)}} \quad [B.10]$$

$$Q_{\max(c)} = \sum_{1}^{j} Q_{cb(i)} + \frac{Q_{cb(i)}\left(T_s - T_{cs(i)}\right)}{\eta_{cc(i)} T_{cs(i)}} \quad [B.11]$$

Where $Q_{hb(i)}$ is the heating demands for building [i],
$Q_{cb(i)}$ is the cooling demands for building [i],
$T_{hs(i)}$ is the preferred hot water supply temperature for building [i],
$T_{cs(i)}$ is the preferred hot water supply temperature for building [i],
T_s is the supply temperature of the UD-LTTN,
$\eta_{cc(i)}$ is the Carnot Efficiency for the cooling heat pump at building [i],
$\eta_{hc(i)}$ is the Carnot Efficiency for the heating heat pump at building [i],
k is the number of buildings consecutively connected to piping network requiring heating
j is the number of buildings consecutively connected to piping network requiring cooling

The derivation for $Q_{\max(s)}$ is very similar to the derivation for $Q_{\max(h)}$ and $Q_{\max(c)}$ except that the initial relationship describes the system rather than a group of consecutive buildings. For this relationship, we are considering the total absolute difference between the energy taken from the loop and the energy supplied. This value can be described by equation [B.12].

$$Q_{\max(s)} = \sum_{1}^{n} \left| Q_{hl(i)} - Q_{cl(i)} \right| \quad [B.12]$$

Where $Q_{hl(i)}$ is the total energy removed from the loop in order to heat building [i],
$Q_{cl(i)}$ is the total energy removed from the loop in order to cool building [i],
n is the number of buildings within the community.

This measurement of $Q_{\max}$ is very important for when UD-LTTN systems are in predominantly heating or cooling, as it describes the overall trend of the system. Like before, substituting in equations [B.5], [B.8] and [B.9] allows for the measurement to be described by either equipment coefficient of performance [B.13] or Carnot cycles and Carnot efficiencies [B.14]

$$Q_{\max(s)} = \sum_{1}^{n} \left| \left(Q_{hb(i)} - \frac{Q_{hb(i)}}{COP_{h(i)}} \right) - \left(Q_{cb(i)} + \frac{Q_{cb(i)}}{COP_{c(i)}} \right) \right| \quad [B.13]$$

$$Q_{\max(s)} = \sum_{1}^{n} \left| \left(Q_{hb(i)} - \frac{Q_{hb(i)} \left(T_{hs(i)} - T_s \right)}{\eta_{hc(i)} T_{hs(i)}} \right) - \left(Q_{cb(i)} + \frac{Q_{cb(i)} \left(T_s - T_{cs(i)} \right)}{\eta_{cc(i)} T_{cs(i)}} \right) \right| \quad [B.14]$$

$Q_{hb(i)}$ is the heating demands for building [i],
$Q_{cb(i)}$ is the cooling demands for building [i],
$T_{hs(i)}$ is the preferred hot water supply temperature for building [i],
$T_{cs(i)}$ is the preferred hot water supply temperature for building [i],
T_s is the supply temperature of the UD-LTTN,
$COP_{c(i)}$ is the coefficient of performance for the cooling heat pump at building [i],
$COP_{h(i)}$ is the coefficient of performance for the heating heat pump at building [i],
$\eta_{cc(i)}$ is the Carnot Efficiency for the cooling heat pump at building [i],
$\eta_{hc(i)}$ is the Carnot Efficiency for the heating heat pump at building [i],
n is the number of buildings within the community

The final equation [B.15] does not require a derivation. Its purpose is to compare each measure of $Q_{\max(h)}$, $Q_{\max(c)}$ and $Q_{\max(s)}$ to determine which value is the largest. This value can then be substituted into equation [B.1] as $Q_{\max}$ and can be used to calculate the most stable value of $\dot{m}$.

$$Q_{max} = MAX([Q_{\max(s)}],[Q_{\max(h)}],[Q_{\max(c)}]) \quad [B.15]$$

Appendix D: Modelica Storage Models

To model the integration of decentral storage at the ETS of a UD-LTTN system, two additional models have been created. The first is a revision of the UD-LTTN ETSH model, and the second is an ETS controller that optimizes the charging and discharging of the decentralized storage units.

D.1 ETSHwStorage

The ETSHwStorage model builds off the ETSH models to include a stratified storage tank from the AixLib Modelica Library [63]. This storage tank is behind the heat pump, and as such revisions were required between the heat pump interface and the simulated building source and sink ports. Instead of a singular connection, now there are two connections from the simulated building source and sink; one to the heat pump, and one to the stratified storage tank (Figure 49).

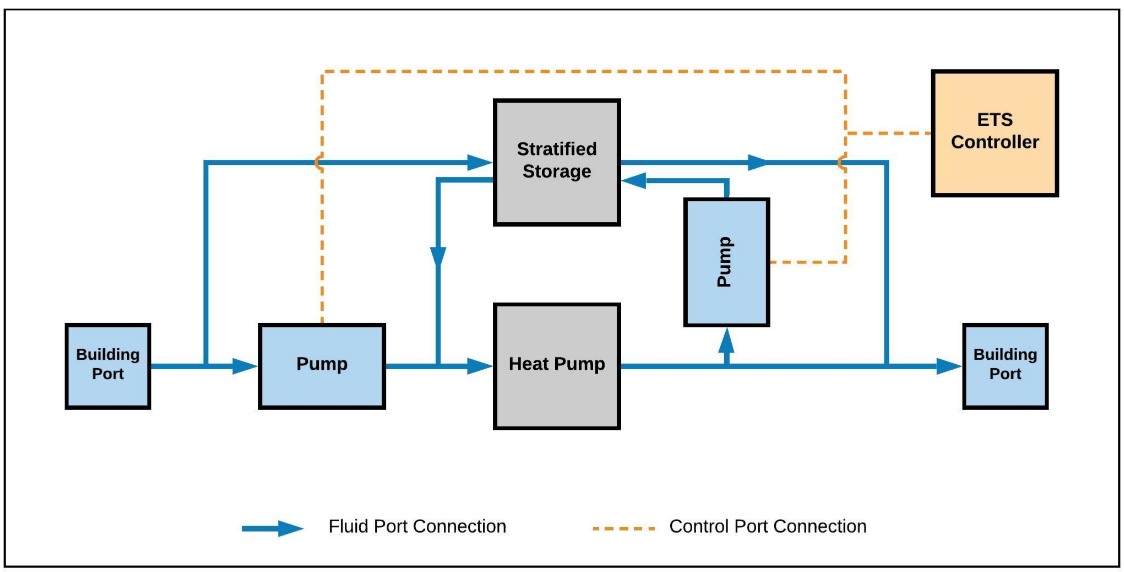

Figure 49 ETSHwStorage Model Revisions

In this way, the building's demand can be fulfilled by either the heat pump or the storage tank either simultaneously or separately. Additionally, a third connection between the heat pump and the storage tank is included. This piping connections enables the charging of the stratified tank and is designed so that the charging process is counterflow to the discharge process. These three connections allow for design flexibility and enable three main modes of operations:

- **Mode One:** Using the Heat Pump to supply all of the building's demands.
- **Mode Two:** Using the Storage Tank to supply all of the buildings. This mode can run concurrently with Mode One in order to maximize waste energy consumption and minimize additional generation requirements.
- **Mode Three:** Using the Heat Pump to charge the storage tank. This mode can run in concurrently with Mode One if the heat pump has a large enough capacity.

While the same supply pump supplies mode One and Two, an additional pump is included for Model Three that enables counterflow charging. Since the motivation for this model was to capture excess waste energy from the UD-LTTN thermal network, this storage tank was added to the ETSH model. The inclusion of a storage tank increases the complexity of the ETSH model. This, in turn, results in an increased number of equations, with the revised ETSHwStorage model having 1217 unique equations, compared to base ETSH model's 396. A large reason for this increase is the sub-model ETSController, which is responsible for controlling the pumps and ensuring balanced operation during all three different modes of operation.

D.2 ETSopt

The addition of storage increases the complexity of the UD-LTTN system control strategy. With this increased complexity comes the potential of increased performance as the system more effectively utilizes the waste energy captured from TDERs. To facilitate this next stage of research, the ETSopt model provides a means to control each ETS's modes of operation from a centralized location. This centralized control is important, because whether an ETS discharges or charges a decentralized storage tank will depend on the demands within the entire community. Although localized control strategies are possible, community-wide strategies increase the potential for sharing energy between buildings and thus decrease community-wide energy utilization. Hence, the ETSopt communicates with each ETS using a control port and can make real-time control decisions for each simulated time step.

To facilitate this decision-making process, the ETSopt model communicates with various temperature and mass flow sensors within the ETS models to determine the state of the UD-LTTN system. This process includes determining which nodes are capturing waste energy, as well as which nodes have high heating demands. Based on this information, it can then dispatch each ETS Controller to operate in a combination of either Mode One, Two or Three. This control platform was designed to give future researchers maximum flexibility when investigating the potential of decentralized storage, and will hopefully lead to future breakthroughs in the UD-LTTN research space.