A Comparative Analysis of Energy Performance of Ultra-Low Temperature District Heating and Cooling Networks with Different Substation Configurations

Yuhang Zhang
Student Member ASHRAE

Mingzhe Liu, PhD
Full Member ASHRAE

Zheng O'Neill, PhD, PE
Fellow ASHRAE

Jin Wen, PhD
Fellow ASHRAE

ABSTRACT

This study aims to explore the differences in the energy performance among ultra-low temperature district heating and cooling (ULTDHC) networks with different substation configurations. Three substation configurations, including free cooling (using heat exchangers only for substation cooling), active cooling (using chillers only for substation cooling), and hybrid cooling (utilizing both chillers and heat exchangers for substation cooling), are investigated through a simulation-based case study in Atlanta, GA. A detailed ULTDHC system model is developed using Modelica. The simulation results indicate that without integrating the sewage water, compared to the system with active cooling configuration, the system with free/hybrid cooling configuration exhibits annual electric energy savings of 5.5% for radiant systems and 2.6% for all-air systems, respectively. However, when the excess waste heat from the sewage water is recycled, the free cooling configuration performs the poorest among the three. In comparison to the system with free cooling, the system with hybrid cooling achieves energy savings of 4.0% for radiant systems and 4.7% for all air systems. These findings reveal that although substation free cooling makes it possible to reduce the energy consumed by the substation cooling process, the overall system performance varies depending on multiple factors such as the availability of thermal energy sources and building-side HVAC system requirements. In addition, the simulation results underscore that network operating temperature control plays a crucial role in the system's performance. Therefore, detailed system analyses are recommended to guide the selection of the most suitable configuration and temperature control settings during ULTDHC system design.

INTRODUCTION

In recent years, ULTDHC (ultra-low temperature district heating and cooling) networks have emerged as a promising technology to reduce building energy consumption and carbon emissions. It is characterized by its close-to-ground level

Yuhang Zhang is a Ph.D. student in the J. Mike Walker '66 Department of Mechanical Engineering at Texas A&M University. **Dr. Mingzhe Liu** is a postdoctoral researcher in the J. Mike Walker '66 Department of Mechanical Engineering at Texas A&M University. **Dr. Zheng O'Neill** is J. Mike Walker '66 Associate Professor in the J. Mike Walker '66 Department of Mechanical Engineering at Texas A&M University. **Dr. Jin Wen** is Professor in the Department of Civil, Architectural, and Environmental Engineering at Drexel University.

operating temperature (i.e., <40℃/104°F) and its capability to provide simultaneous heating and cooling through decentralized heat pumps. Compared to traditional district heating and cooling networks, ULTDHC networks offer the potential for significantly enhanced energy efficiency as they leverage the synergies of hybrid heating and cooling within the district. In addition, the lower operational temperature makes it possible to integrate more low-grade thermal energy sources and reduce thermal losses through the grid (Lund et al. 2021).

A typical ULTDHC network comprises three major components, including **substations, balancing units, and pipelines**. Substations serve as the connection between the user facilities and the network. Its main function is to adjust the network water temperatures to the specific temperature requirement of each building and provide heating and cooling to end users. Notably, in ULTDHC systems, substations are often referred to as "prosumers", as they can supply thermal energy to the network and extract thermal energy from it (Sommer et al. 2020). This dual capability enhances the system flexibility and efficiency. The balancing unit is instrumental in managing and balancing heat within the network. Their primary role is to maintain the network temperature by addressing the excessive heat imbalances in the network. The selection of thermal energy sources employed in the balancing unit generally depends on the local availability and specific temperature requirements of the network. The balancing units ensure the reliable and effective operation of the ULTDHC system. A network of pipes forms the physical infrastructure that connects substations and balancing units. These pipelines facilitate the distribution of both warm and cold water to all end users within the ULTDHC network. According to the number of pipelines at different temperature levels and the medium flow direction in the pipelines, ULTDHC systems can be classified into multiple categories (Buffa et al. 2019). This study focuses on one of the most common system configurations known as two-pipe bidirectional parallel network. In this configuration, the flow direction within the pipelines can change depending on the load conditions, thus deviating from the conventional supply and return pipe arrangement. Instead, the distribution pipes are categorized into warm pipes and cold pipes based on their operating temperature levels. Typically, a consistent temperature difference is maintained between the warm and cold pipes.

As for the specifics of substations, there are three primary substation types based on the heating and cooling devices, as illustrated in Figure 1. One of the most common setups is known as active heating/cooling. In this setup, both heat pumps and chillers are installed within the substation, allowing for a versatile approach for heating and cooling provisions. The operation involves heat pumps extracting the warm water from warm pipes and releasing the cold water into cold pipes to deliver heating. Simultaneously, chillers extract the cold water from cold pipes and release the warm water into warm pipes to provide cooling. The inclusion of both heat pumps and chillers allows for precise modulations of the network temperature, reducing the need to directly adjust the network's operating temperature to match end users' requirements. This, in turn, enhances the flexibility in network temperature controls. As a result, this configuration has gained extensive use in various research projects and practical applications(Blacha et al. 2019; Bilardo et al. 2021; Bu et al. 2023).

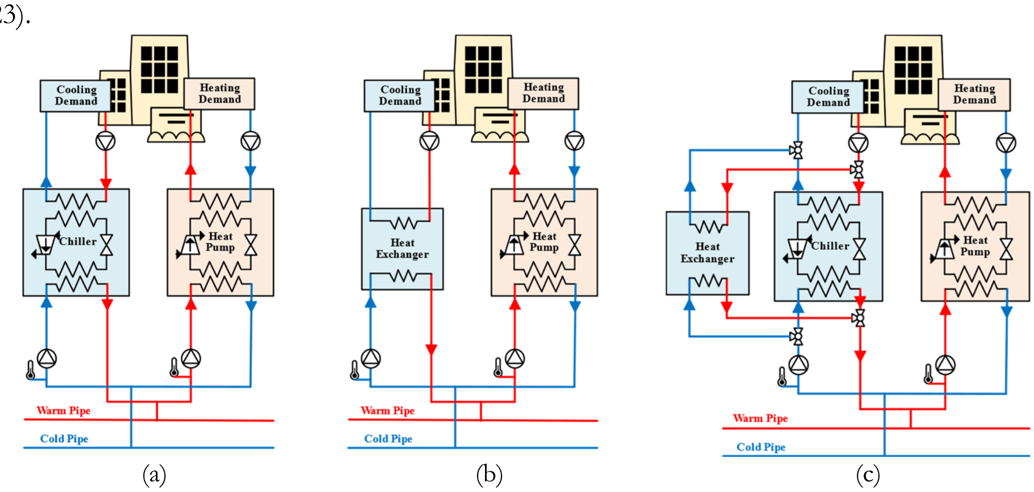


Figure 1 Details of different substation configurations. (a) active cooling (b) free cooling (c) hybrid cooling.

Considering the typically low operating temperatures of ULTDHC systems, a different setup termed "free cooling" or "compressor-less cooling" has been introduced, replacing traditional chillers with heat exchangers to directly provide cooling to substation users (Gautier, Wetter, and Sulzer 2022). This setup offers several advantages compared with the aforementioned active cooling configuration. Since the heat transfer through the heat exchanger is inherently more energy-efficient compared to mechanical cooling, the setup significantly reduces cooling energy consumption at the substations. In addition, as no chillers are needed, it leads to substantial reductions in both initial and maintenance costs for the substations. Research conducted by Abugabbara et al. (2021) demonstrated that the adoption of free cooling heat exchangers could result in savings of up to 10% in the total annual energy usage when applied to a cluster of 11 buildings. Gautier et al. (2022) provided evidence that indoor thermal conditions can be effectively maintained within an acceptable range even during a hot week by relying solely on heat exchangers for cooling while consuming only half the electrical energy compared to standard chiller operations.

However, the application of substation free cooling necessitates maintaining the operating temperature within a comparatively lower range to ensure the feasibility of provide cooling directly through heat exchangers compared with the substation active cooling configuration. If the substation free cooling configuration is employed, the upper limit of the system's operating temperature is largely dependent on the HVAC systems within the buildings and typically cannot exceed 20℃ (68°F) (Zarin Pass, Wetter, and Piette 2018; Sommer et al. 2020; Quirosa, Torres, and Chacartegui 2022). A study conducted by Quirosa et al. (2022) compared five ULTDHC cases with different temperature limits, one of which had a maximum cold pipe temperature limit of 14℃ (57°F) to enable a constant free cooling, while the others had this restriction removed. The simulation results indicated that while the free cooling reduced substation requirements, it also decreased the system storage capacity and increased energy consumption from the energy grid. Gautier et al. (2022) investigated the effects of relying solely on free cooling on plant selection and sizing, revealing that a geothermal bore field would need to be significantly larger in a system with free cooling compared to one with active cooling, highlighting the constraints imposed on thermal energy sources.

To address the temperature restrictions associated with substation free cooling, researchers have introduced a hybrid configuration (Samuel Henchoz et al. 2016; Wirtz et al. 2021; Abugabbara, Javed, and Johansson 2022). In this arrangement, both chillers and heat exchangers are installed within substations. Typically, a designated switch temperature serves as the threshold between the free cooling mode and active cooling mode. When the cold pipe temperature drops below the switch temperature, the network engages free cooling, and the chillers are deactivated. Conversely, when the cold pipe temperature rises above the switch point, the chillers take over for cooling, and the heat exchanger is bypassed. This configuration offers the advantage of having both free cooling and active cooling options. However, it does entail increased initial construction and maintenance costs due to the installation of both chillers and heat exchangers within substations.

To date, there remains a scarcity of studies elucidating the disparities in the ULTDHC system performance contingent on various substation configurations. Thus, this study endeavors to fill this gap by conducting a simulation-based analysis, assessing the influence of three distinct substation configurations on the system performance across a range of design scenarios. A detailed ULTDHC system model has been developed using Modelica. The outcomes of this study are poised to provide valuable insights for designers grappling with the task of selecting the most suitable configuration for ULTDHC systems.

METHODOLOGY

Case study

We conducted a case study in Atlanta, GA, utilizing a ULTDHC network to investigate the energy performance disparities associated with different substation configurations. The ULTDHC network comprises three substations and a centralized balancing unit, with its key components outlined in Figure 2. The study encompasses three commercial building types: large office buildings, hospitals, and high-rise apartments, each representing a dedicated user for one substation. The load profiles for these buildings come from simulations of the DOE prototype building models (The U.S. Department of Energy (DOE) 2023) using EnergyPlus. The domestic hot water load and space heating load are aggregated together as the total heating load. To ensure a balanced load representation across the diverse building types, the load of the high-rise apartment is scaled up by a factor of 10. The cumulative annual cooling demand totals 45540 GJ (12.65 GWh), while the total annual heating demand is 13788 GJ (3.83 GWh). Figure 3 illustrates the hourly heating and cooling load profile throughout the year.

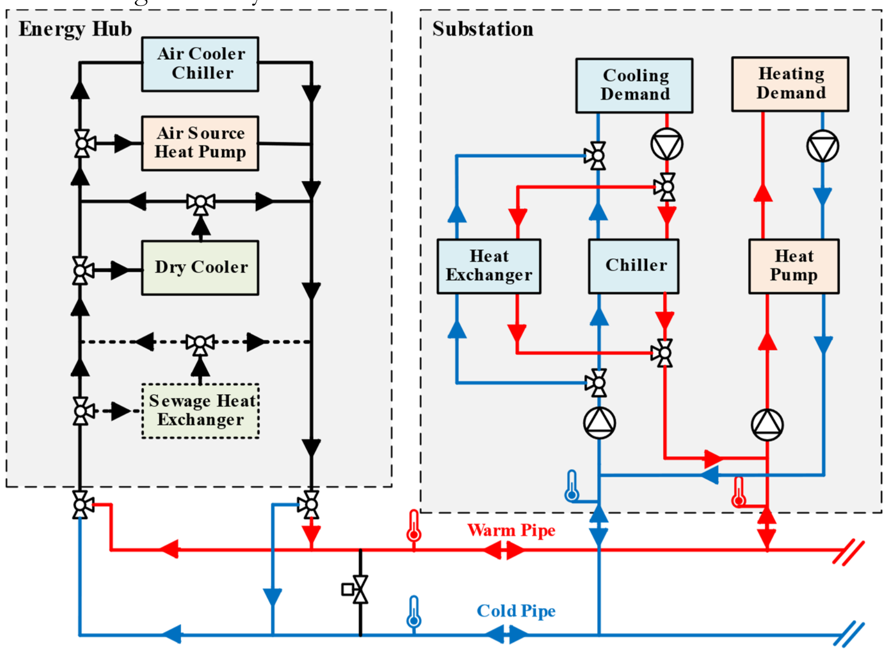


Figure 2 Schematic diagram of the main components used in the ULTDHC system.

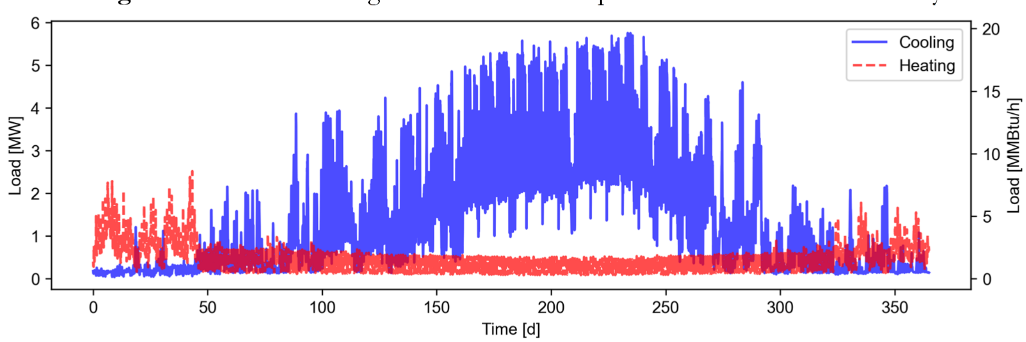


Figure 3 Hourly heating and cooling load profile.

Four distinct scenarios are explored in our study, encompassing two balancing unit configurations and two building HVAC system types. In the balancing unit configuration, the base setting incorporates an air-cooled chiller, an air source heat pump, and a dry cooler. The other setting, built upon the base configuration, integrates a heat exchanger to recover the waste heat from the sewage water. For this preliminary study, we assume a constant sewage water temperature of 20℃ (68°F) year-round.

The choice of building HVAC system types primarily affects the network's operating temperature requirements when considering the substation free cooling. Two building HVAC system types are considered, including radiant heating and cooling systems and all air systems. For radiant systems, the building chilled water supply temperature is set at 18℃ (64°F). Considering the heat exchangers' heat transfer capabilities, 16℃ (60°F) is set as the maximum allowable cold pipe temperature for the substation free cooling configuration and as the switch temperature setpoint for the substation hybrid cooling configuration. In the case of all-air systems, the building chilled water supply temperature is maintained at 10°C (50°F), resulting in 8°C (46°F) being the maximum allowable cold pipe temperature for substation free cooling configuration and the switch temperature setpoint for substation hybrid cooling configuration.

Setup of the simulation environment

To simulate the aforementioned scenarios, a comprehensive virtual testbed for ULTDHC systems was developed using the Modelica language. Modelica is an open-standard, object-oriented modeling language widely employed in engineering and scientific domains for modeling intricate physical systems (Mattsson and Elmqvist 1997). It has gained extensive use in modeling and simulating district energy systems (Schweiger et al. 2017; Zarin Pass, Wetter, and Piette 2018; Abugabbara, Javed, and Johansson 2022). The basic components utilized in this testbed primarily originate from the Modelica Buildings Library, which offers dynamic simulation models for building and district energy systems (Wetter et al. 2014). As outlined in the introduction section, the system is composed of substations, balancing units, and pipelines. This section provides a brief overview of the modeling process for the primary components within ULTDHC systems.

Substation: As shown in Figure 2, the substation model comprises a heat pump for handling the heating demand, a chiller and a heat exchanger for handling the cooling demand, along with two distributed pumps for circulation. Building load profiles serve as input data for the substation. All three substation configurations are simulated by the same substation model through assigning different control strategies to the two 3-way diverter valves located in front of the substation. For the permanent active cooling, the 3-way diverter valves exclusively direct the cold pipe water into the chillers, permanently bypassing the heat exchangers. Conversely, to achieve a permanent free cooling, the adjustment of the 3-way diverter valves ensures that the cold pipe water can only enter the heat exchangers, with the chillers permanently turned off. To achieve the hybrid cooling, the flow direction is dynamically adjusted based on real-time temperatures from the substation's connection with the cold pipe. The coefficient of performance (COP) for both chillers and heat pumps can be calculated by Eq. (1):

$$COP = \eta_{Carnot} \times \frac{T_{cond}}{T_{cond} - T_{evap}} \tag{1}$$

where T_{cond} is the temperature of the condenser, K; T_{evap} is the temperature of the evaporator, K; and η_{Carnot} is Carnot effectiveness, which is fixed at a constant value of 0.4 in this preliminary study.

Balancing unit: Two balancing unit configurations are considered. Both the dry cooler and sewage water can be used as heating and cooling sources. When the network temperature exceeds the predefined limits, the balancing unit is activated to maintain the network temperature within the specified range. To fully take advantage of free thermal energy sources, priority is given to the sewage water heat exchanger first, followed by the dry cooler, and finally the refrigerant-based heating and cooling devices in the hub. The COP for the refrigerant-based heating and cooling devices can also be calculated using Eq. (1).

Pipeline: The distribution pipe model employed in the study is primarily based on Abugabbara et al. (2022). This pipe model is capable of simulating both hydraulic pressure drops and heat transfer to the surroundings. In the analyzed system, each pipeline is designed to have a length of 300m (984 ft). The pipe diameters are determined using the criteria that pressure losses should be 100 Pa per meter (1.0 ft of water per 100 ft) at design flow rates (ASHRAE 2013).

The Modelica diagram view of the studied ULTDHC system is depicted in Figure 4. Key parameters employed in the ULTDHC system are presented in Table 1.

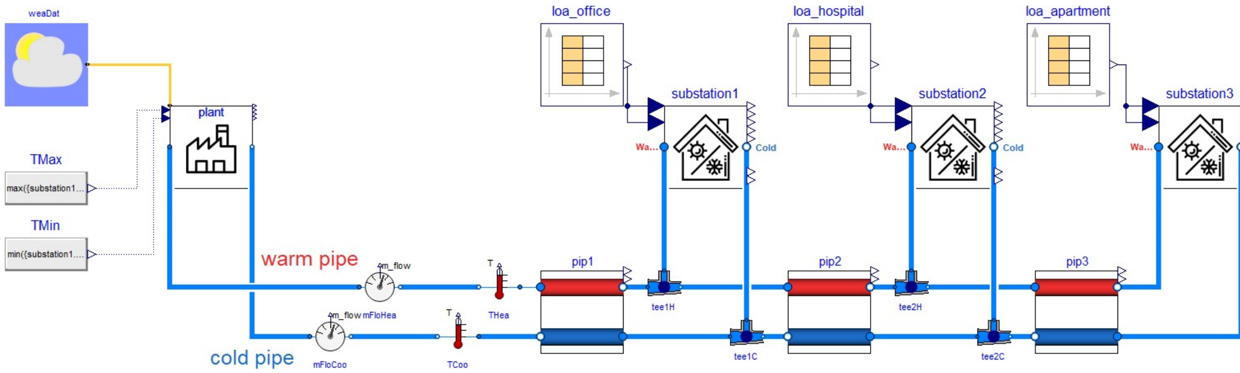


Figure 4 The Modelica diagram view of the studied ULTDHC system.

Table 1. Key Parameters Employed in the ULTDHC System

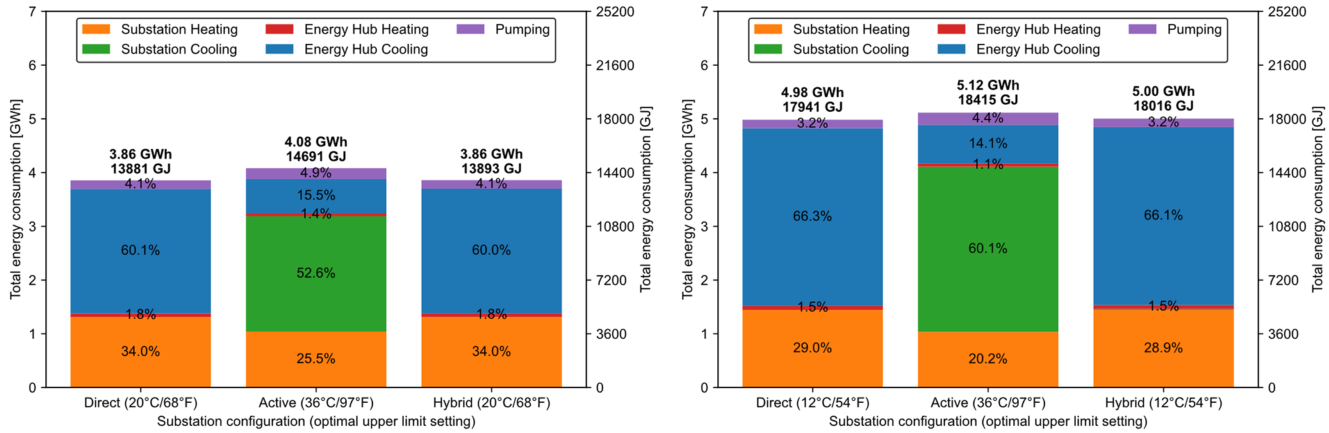
Parameter	Value
Building chilled water supply temperature setpoint (radiant/all-air system)	18°C (64°F)/10°C (50°F)
Building hot water supply temperature setpoint	55°C (131°F)
Temperature range of warm lines	[8°C (46°F), 40°C (104°F)]
Temperature range of cold lines	[4°C (39°F), 36°C (97°F)]
Design temperature differential	4°C (7°F)
Carnot efficiency	0.4
Heat exchanger effectiveness	0.8
Length of each pipe	300m (984 ft)
Nominal pressure drops per length	100Pa/m (1.0 ft of water per 100 ft)

In each of the aforementioned scenarios of this case study, three substation configurations are implemented. To determine the optimal temperature settings for each substation configuration, various temperature spreads were tested. The lower temperature limit is fixed at 4°C (39°F) to prevent freezing, while the upper limit is varied from 8°C (46°F) to 40°C (104°F), at an interval of 4°C (7°F). For each configuration, the temperature setting that results in the lowest total system energy consumption is selected as the optimal setting and shown in Figure 5 and Figure 6. Note that for the substation free cooling configuration, the range of settings is more limited compared to the other two configurations due to the operating temperature constraints of the system with free cooling. All simulations are conducted over one year, utilizing the CVODE solver with a tolerance of 1×10^{-6}.

RESULTS

Figure 5 and Figure 6 depict the annual system energy consumption for those four studied scenarios. To visualize the impact of different substation configurations on the major energy components of the ULTDHC system, the total system energy consumption is divided into five parts: substation heating, substation cooling, balancing unit heating, balancing unit cooling, and pumping.

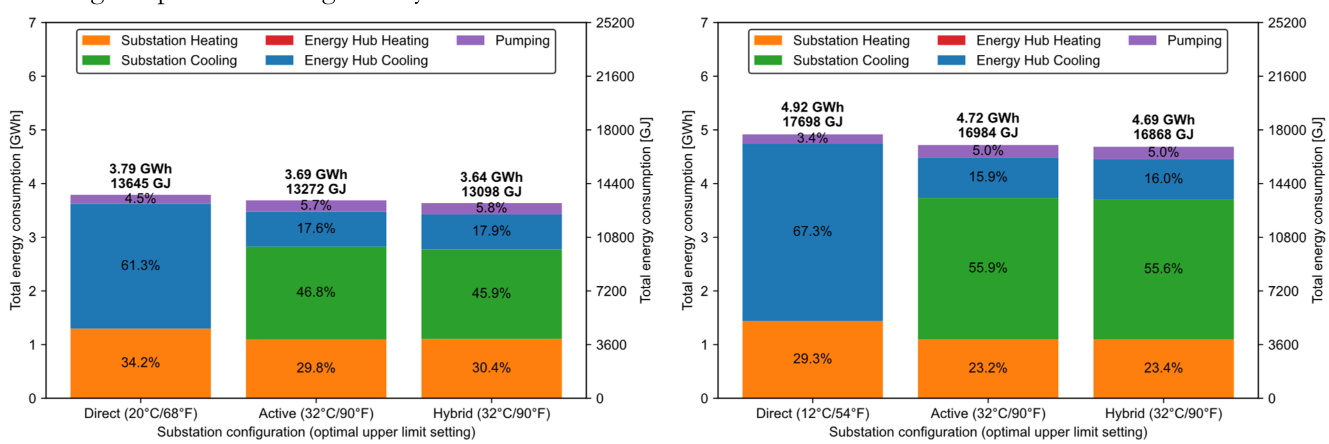
As reflected in Figure 5, in the absence of waste heat integration from the sewage water, the ULTDHC system with substation direct/hybrid cooling configuration demonstrates a superior energy performance compared to the system with only active cooling. The optimal setting for both free cooling and hybrid cooling occurs when the upper limit of the cold pipe temperature equals the maximum temperature that allows a free cooling through heat exchangers. Within this temperature limit, the system with hybrid cooling is essentially equivalent to the system with free cooling, as the chiller remains unused. Compared to the system with active cooling, the system with direct/hybrid cooling achieves a 5.5% energy saving for radiant systems and a 2.6% energy saving for all-air systems, despite consuming more energy in the balancing unit cooling and substation heating due to the lower network operating temperature. The primary source of energy savings is the substantial reduction in substation cooling energy consumption, which accounts for more than half of the total energy usage.



(a) (b)

Figure 5 Total energy consumption of the ULTDHC system without the integration of sewage water. (a) Radiant heating and cooling systems. (b) All air systems.

With the integration of the waste heat from sewage water, Figure 6 illustrates that while all system performance improves compared to the case when waste heat from sewage water is not integrated, the system with hybrid/active cooling shows more improvement than the system with free cooling. This difference arises because the temperature of sewage water is higher than the maximum allowable operating temperature of the system with free cooling, allowing it to provide heating but not cooling. In contrast, for the system with active/hybrid cooling, which has a wider allowable operating temperature range, sewage water can serve as both a heating and cooling source, resulting in a reduced energy consumption for the balancing unit heating and cooling. This shift leads to changes in the optimal substation configuration. The optimal system energy performance is achieved when using the hybrid cooling configuration with an upper limit of 32°C (90°F), while the system with free cooling becomes the least efficient option. In comparison to the system with free cooling, the system with hybrid cooling achieves energy savings of 4.0% for radiant systems and 4.7% for all air systems. The energy performance of the system with active cooling is slightly inferior to that of the system with hybrid cooling, primarily due to increased substation cooling energy use when the operating temperature is low enough to provide cooling directly.



(a) (b)

Figure 6 Total energy consumption of the ULTDHC system with the integration of sewage water. (a) Radiant heating and cooling systems. (b) All air systems.

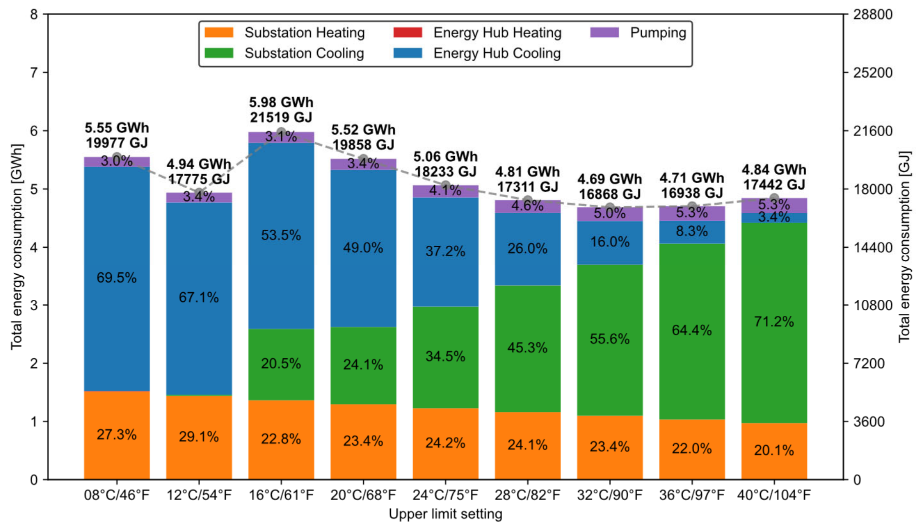


Figure 7 Total energy consumption of the ULTDHC system with sewage water integration and hybrid cooling at different network operating temperature upper limit settings.

Another noteworthy observation is the influence of temperature settings on the ULTDHC system energy performance. As depicted in Figure 5 and Figure 6, the optimal temperature settings vary across different scenarios. Figure 7 provides further insights into the total energy consumption of the system with sewage water integration and hybrid cooling at different upper limit settings of network operating temperatures. The figure illustrates that as the network operating temperature upper limit setting is raised, the energy used for substation heating and balancing unit cooling decreases, while the energy used for substation cooling increases. These variations result in the total system energy use displaying two local minimum values with the change in the upper limit setting. One occurs at the switch temperature between the active cooling and free cooling modes, which is also the optimal setting for the system with free cooling. The other occurs when the upper limit equals 32°C (90°F), which is also the optimal setting for the system with active cooling. This underscores the strong impact of network temperature control on the ULTDHC system performance. Each configuration requires suitable coordination with a temperature control strategy to achieve the optimal system performance.

CONCLUSIONS

This preliminary study summarizes and compares three common substation configurations applied in ULTDHC (ultra-low temperature district heating and cooling) systems: active cooling, free cooling, and hybrid cooling. Detailed ULTDHC system models are developed using Modelica to implement these configurations in multiple scenarios. The following conclusions can be drawn from the study:

1. Substation free cooling, under certain circumstances, is able to improve the overall system performance by reducing substation cooling energy consumption at the substation. However, it also imposes restrictions on the network operating temperature range, which can hinder the integration of some low-grade thermal energy sources, potentially not benefiting the overall system energy efficiency.
2. If energy consumption is the sole performance indicator, the hybrid cooling configuration is the optimal choice among the three common substation setups, as it supports both active cooling and free cooling. However, due to its higher installation and maintenance costs, a payback analysis is recommended before making a final decision.
3. ULTDHC networks show varying system performance with different configurations and temperature control settings. Therefore, for ULTDHC systems integrated with multiple thermal energy sources, a comprehensive analysis is advisable to select the appropriate substation configuration and temperature control settings.

ACKNOWLEDGMENTS

This work is partly supported by the National Science Foundation [Grant Number: 2309030].

REFERENCES

Abugabbara, Marwan, Saqib Javed, and Dennis Johansson. 2022. "A Simulation Model for the Design and Analysis of District Systems with Simultaneous Heating and Cooling Demands." *Energy* 261 (December): 125245. https://doi.org/10.1016/j.energy.2022.125245.

Abugabbara, Marwan, Jonas Lindhe, Saqib Javed, Hans Bagge, and Dennis Johansson. 2021. "Modelica-Based Simulations of Decentralised Substations to Support Decarbonisation of District Heating and Cooling." In *Energy Reports*, 7:465–72. The 17th International Symposium on District Heating and Cooling. https://doi.org/10.1016/j.egyr.2021.08.081.

ASHRAE. 2013. *District Heating Guide*. Atlanta, GA: ASHRAE.

Bilardo, Matteo, Federico Sandrone, Guido Zanzottera, and Enrico Fabrizio. 2021. "Modelling a Fifth-Generation Bidirectional Low Temperature District Heating and Cooling (5GDHC) Network for Nearly Zero Energy District (nZED)." *Energy Reports* 7 (November): 8390–8405. https://doi.org/10.1016/j.egyr.2021.04.054.

Blacha, Tobias, Michael Mans, Peter Remmen, and Dirk Müller. 2019. "Dynamic Simulation Of Bidirectional Low-Temperature Networks - A Case Study To Facilitate The Integration Of Renewable Energies." In , 3491–98. Rome, Italy. https://doi.org/10.26868/25222708.2019.210670.

Bu, Ting, Rui Fan, Bin Zheng, Kexin Sun, and Yibing Zhou. 2023. "Design and Operation Investigation for the Fifth-Generation Heating and Cooling System Based on Load Forecasting in Business Districts." *Energy and Buildings* 294 (September): 113243. https://doi.org/10.1016/j.enbuild.2023.113243.

Buffa, Simone, Marco Cozzini, Matteo D'Antoni, Marco Baratieri, and Roberto Fedrizzi. 2019. "5th Generation District Heating and Cooling Systems: A Review of Existing Cases in Europe." *Renewable and Sustainable Energy Reviews* 104 (April): 504–22. https://doi.org/10.1016/j.rser.2018.12.059.

Gautier, Antoine, Michael Wetter, and Matthias Sulzer. 2022. "Resilient Cooling through Geothermal District Energy System." *Applied Energy* 325 (November): 119880. https://doi.org/10.1016/j.apenergy.2022.119880.

Lund, Henrik, Poul Alberg Østergaard, Tore Bach Nielsen, Sven Werner, Jan Eric Thorsen, Oddgeir Gudmundsson, Ahmad Arabkoohsar, and Brian Vad Mathiesen. 2021. "Perspectives on Fourth and Fifth Generation District Heating." *Energy* 227 (July): 120520. https://doi.org/10.1016/j.energy.2021.120520.

Mattsson, Sven Erik, and Hilding Elmqvist. 1997. "Modelica - An International Effort to Design the Next Generation Modeling Language." *IFAC Proceedings Volumes*, 7th IFAC Symposium on Computer Aided Control Systems Design (CACSD '97), Gent, Belgium, 28-30 April, 30 (4): 151–55. https://doi.org/10.1016/S1474-6670(17)43628-7.

Quirosa, Gonzalo, Miguel Torres, and Ricardo Chacartegui. 2022. "Analysis of the Integration of Photovoltaic Excess into a 5th Generation District Heating and Cooling System for Network Energy Storage." *Energy* 239 (January): 122202. https://doi.org/10.1016/j.energy.2021.122202.

Quirosa, Gonzalo, Miguel Torres, V. M. Soltero, and Ricardo Chacartegui. 2022. "Analysis of an Ultra-Low Temperature District Heating and Cooling as a Storage System for Renewable Integration." *Applied Thermal Engineering* 216 (November): 119052. https://doi.org/10.1016/j.applthermaleng.2022.119052.

Samuel Henchoz, Patrick Chatelan, François Maréchal, and Daniel Favrat. 2016. "Key Energy and Technological Aspects of Three Innovative Concepts of District Energy Networks." https://doi.org/10.1016/j.energy.2016.05.065.

Schweiger, Gerald, Per-Ola Larsson, Fredrik Magnusson, Patrick Lauenburg, and Stéphane Velut. 2017. "District Heating and Cooling Systems – Framework for Modelica-Based Simulation and Dynamic Optimization." *Energy* 137 (October): 566–78. https://doi.org/10.1016/j.energy.2017.05.115.

Sommer, Tobias, Matthias Sulzer, Michael Wetter, Artem Sotnikov, Stefan Mennel, and Christoph Stettler. 2020. "The Reservoir Network: A New Network Topology for District Heating and Cooling." *Energy* 199 (May): 117418. https://doi.org/10.1016/j.energy.2020.117418.

The U.S. Department of Energy (DOE). 2023. "Prototype Building Models | Building Energy Codes Program." Prototype Building Models. September 6, 2023. https://www.energycodes.gov/prototype-building-models#Commercial.

Wetter, Michael, Wangda Zuo, Thierry S. Nouidui, and Xiufeng Pang. 2014. "Modelica Buildings Library." *Journal of Building Performance Simulation* 7 (4): 253–70. https://doi.org/10.1080/19401493.2013.765506.

Wirtz, Marco, Lisa Neumaier, Peter Remmen, and Dirk Müller. 2021. "Temperature Control in 5th Generation District Heating and Cooling Networks: An MILP-Based Operation Optimization." *Applied Energy* 288 (April): 116608. https://doi.org/10.1016/j.apenergy.2021.116608.

Zarin Pass, R., M. Wetter, and M. A. Piette. 2018. "A Thermodynamic Analysis of a Novel Bidirectional District Heating and Cooling Network." *Energy* 144 (February): 20–30. https://doi.org/10.1016/j.energy.2017.11.122.