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# Network configurations for implemented low-temperature district heating

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ABSTRACT

This paper presents the findings and conclusions from an inventory of network configurations implemented in several early projects concerning low-temperature district heating systems implemented in both existing and new networks. The main findings are presented for each configuration group, including configuration layouts, typical temperature levels and several implemented installation examples, together with the advantages and disadvantages of each network configuration. In the assessment, a classification system comprising six different groups of typical network configurations was identified for low-temperature heat distribution. Together with eight variants within three of these six groups, fourteen possible network configurations were identified for low-temperature district heating. The main feature became the choice between a cold or warm network for the heat distribution, while the suitability of each network configuration depends on the temperatures of the available heat sources.


## 1. Introduction

### 1.1. The context

The decarbonisation of both existing and new district heating systems necessitates a revision of traditional heat distribution technology, since this technology was originally developed within a fossil fuel society [1]. At that time, it was easy to create higher temperatures in district heating systems with fossil fuels, so efforts to obtain lower temperature levels were never rewarded, neither in heat distribution networks nor inside buildings.

The definition paper for fourth generation district heating [2] identified three important abilities associated with lower temperature levels. The first ability was to supply low-temperature heat for space heating and hot water to obtain the benefits of a low temperature level. The second ability focused on obtaining low heat distribution losses in networks, while the third ability was to utilise renewable and recycled heat from low-temperature sources. These three abilities increase the efficiency in the three parts of the supply chain (use, distribution and supply) in district heating systems.

The main economic drivers for lower temperatures in heat distribution networks are mainly higher conversion and utilisation efficiencies when using low-temperature heat sources when substituting fossil fuels [3]. The common denominator for many new heat sources, such as solar collectors, heat pumps, geothermal wells, and low-temperature excess heat from chillers, industrial processes, and computer centres, is that they are not based on combustion and cannot easily generate high heat distribution temperatures. Hence, it will be more expensive to use high heat distribution temperatures than using low temperatures. In order to welcome new low-temperature heat sources, it is wise to introduce lower heat distribution temperatures in new networks and reduce heat distribution temperatures in existing networks.

The total cost sensitivity for heat sold can be determined using a cost reduction gradient expressed as annual cost reduction per unit of heat sold and per unit degree of reduced temperature level [4]. For existing systems using mainly fuel combustion in combined heat and power (CHP) plants, cost reduction gradients have been estimated to be slightly above 0.1 euro/MWh per °C [1]. The corresponding gradient for future systems with higher proportions of a non-combustion heat supply have been estimated to be slightly above 0.5 euro/MWh per °C, according to Refs. [5,6]. Hence, the future cost sensitivity for a non-combustion heat supply will be about five times higher than the current sensitivity when the heat supply is dominated by heat recycling from CHP plants.

These insights point to the need for lower heat distribution temperatures in future networks through the development of low-temperature district heating (LTDH). The key knowledge involves how to obtain lower heat distribution temperatures in both existing

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**Abbreviations**

| | |
|---|---|
| CHC | Combined Heating and Cooling |
| CHP | Combined Heat and Power |
| DHC | District Heating and Cooling |
| IEA | International Energy Agency, Paris |
| IEA-DHC | The IEA technology collaboration programme on district heating and cooling |
| IEA-HPT | The IEA technology collaboration programme on heat pumping technologies |
| IEA-SHC | The IEA technology collaboration programme on solar heating and cooling |
| LTDH | Low-Temperature District Heating |

and new district heating systems. However, existing networks are constrained by the applied network configurations already in use, while new networks are associated with more degrees of freedom, so that more suitable network configurations can be applied in the future. An open question is: Which network configurations are suitable for LTDH?

### 1.2. Aim and three research questions

The focus of this paper is to identify suitable network configurations for LTDH that can be used in the implementation of new networks or the expansion of existing networks. The paper aims to provide an overview of network configurations used in early implementations of LTDH based on an extensive inventory and to provide conclusions from this overview. Hence, the following three research questions guide this work:

1. What network configurations have been used in early implementations of LTDH?
2. What are the main features of these network configurations?
3. What are the main conclusions concerning the suitability of the various network configurations?

Hereby, this paper has a strong focus on identifying network configurations that already have been applied in real implemented LTDH projects, being the scientific novelty of this paper. It is not a review paper concerning all published ideas concerning new network configuration for LTDH. Since the main priority is on heat distribution in this paper, less attention is also directed towards heat supply from various low-temperature heat sources and the temperatures affiliated to these sources. That correlation matrix between low-temperature heat supply and low-temperature heat distribution has to be described in another paper.

## 2. Methodology

### 2.1. Inventory

The purpose of the inventory was to find early initiatives of LTDH with respect to heat distribution both in district heating networks and inside buildings. The inventory was organised through several multi-dimensional actions. First, questions were put forward concerning LTDH systems to the national members of the IEA-DHC Executive Committee and to all participants in the IEA-DHC TS2 project devoted to the implementation of LTDH. Second, previous LTDH experiences gained through earlier IEA-DHC projects were identified, such as [7–9]. Third, early implementation cases involving LTDH were identified in some European research projects (such as Cool DH, D2Grids, HeatNet NWE, Life4-HeatRecovery, Lowtemp, Related, Reuseheat, Rewardheat, and Tempo) together with an international research programme (IEA-SHC Task 52) and some national programmes (NextGenerationHeat and Thermaflex in Austria together with Wärmenetze 4.0 in Germany). Fourth, papers about LTDH in scientific journals and conferences were examined. Finally, extensive Internet searches were performed concerning additional LTDH cases.

One important limitation of the inventory was that only networks that used water as a heat carrier were considered. Proposals for network configurations utilizing other heat carriers, such as those presented in Ref. [10], were not included.

The outcome of the inventory comprised 165 implemented, planned, or proposed cases containing initiatives involving networks and buildings from nineteen countries. All identified cases are listed in Section 10.3 of the IEA-DHC guidebook on the implementation of LTDH [1]. Concerning networks, 86 implemented, 44 planned, and 23 proposed cases were identified, providing a total of 153 network initiatives as input to the assessment. Hence, only twelve initiatives were included related to buildings, as networks were the main focus in the inventory.

### 2.2. Vocabulary used in this paper

In order to make this overview transparent and clear, it is vital to define new features and distinguish them from traditional features in DHC systems [11]. It is also important to a make a distinction between technology generations and the technology choices within these generations [12]. In this section, some definitions are provided as vital for understanding the content of this paper.

**Network configuration** is used to describe how the heat distribution is organised in a district heating network with respect to number of parallel pipes used, temperature level applied, flow organisation, and the presence of an additional heat supply in customer substations.

**Low-temperature district heating** (LTDH) refers to all district heating networks having annual average supply temperatures below 70 °C.

**Warm and cold networks** are terms used to label the temperature level in the network with respect to the ability to satisfy customer temperature demands. In warm networks, the supply temperatures are high enough to deliver all heat to meet typical heat demands in buildings without any additional heat supply in the buildings. In cold networks, some additional heat supply is required in the customer buildings to meet typical temperature demands. In low-energy buildings, the typical heat load with the highest temperature demand is the preparation of domestic hot water, requiring a supply temperature of at least 50 °C to generate domestic hot water of 45 °C in a heat exchanger with a long thermal length. Hence, 50 °C is used as the dividing temperature between warm and cold networks. **Low and ultra-low supply temperatures** are expressions for the supply temperatures in warm and cold networks, respectively.

**Combined Heating and Cooling** (CHC) is a label that has been used in recent years for the synergy of reusing heat rejection from a cooling process as a heat supply. Concurrent use of heat and cold is the best condition for this synergy, but heat can also be stored for the winter and cold can be stored for the summer through the same seasonal storage facility. When applying this fundamental synergy to two-pipe systems, it is confusing to use the nomenclature of supply and return temperatures that are used for traditional district heating and cooling systems. Instead, it is more suitable to label these warm and cold temperatures. The **warm temperature** is the supply temperature for the heating process, while it is the return temperature for the cooling process. The opposite is true for the

**cold temperature**. When using the CHC synergy, a source distinction can be made between internal and external cooling processes. In internal cases, the heat comes from the cooling of the same buildings that are heated by the network. By contrast, in external cases, the heat originates from cooling other buildings or processes located close to the heated buildings.

**Delivery and circulation flows** are expressions used for making a distinction between the two principal conditions for the mass flow in all heat distribution systems. The delivery flow brings the heat to each customer substation, while the additional circulation flow is sometimes required for consistently bringing the suitable supply temperature to each customer substation when space heating demands are low. The main aim for circulation flows is to always keep the availability to generate domestic hot water instantaneously in heat exchangers. The purpose with the circulation flow is to counteract reductions of the supply temperature caused by inevitable heat distribution losses. At higher demands of space heating, no additional circulation flows are fundamentally required since the delivery flow provide this service itself. Currently, additional circulation flows are either controlled through the flow control with a temperature setpoint in each substation or uncontrolled by open valves between supply and return pipes in the network.

## 3. Findings from the inventory

An overview of the findings from the inventory of recently implemented, planned, and proposed low-temperature district heating networks is presented in Table 1. This table contains the six main configuration groups that were identified as the common denominators of the networks collected in the inventory. These six configuration groups and the associated variants are explained along with their features in the following sections of this chapter, including configuration layouts, typical temperature levels, advantages, disadvantages, and some implemented and planned cases. Temperature levels for supply and return temperatures are in these descriptions expressed in general as annual time-averaged values.

### 3.1. Classic configurations with warm networks

In the first configuration group, the traditional network configuration from the earlier technology generations is used, but with considerably lower supply and return temperatures. The general Classic configuration is presented in Fig. 1 and consists of a two-pipe heat distribution, normally with one substation in each connected building, but substations can also appear for flats or groups of buildings. This configuration was originally developed and implemented when the heat supply in district heating systems relied on the combustion of fossil fuels, from which high temperatures were readily available. At that time, less attention was directed towards low-temperature heat distribution.

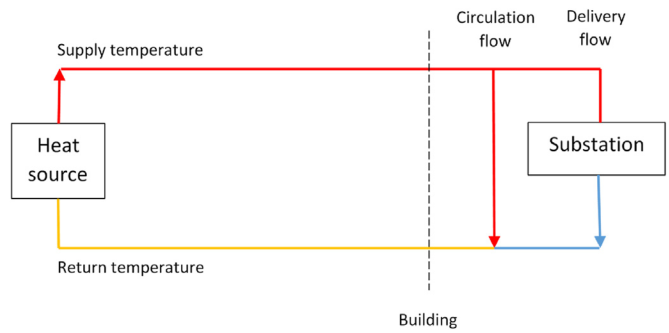


**Fig. 1.** Layout for the Classic configuration in warm networks.

As already stated in the previous chapter, a circulation flow is required to keep a suitable supply temperature when continuous delivery flow is not available, such as during the summer when only intermittent use of domestic hot water appears.

Typical supply temperatures in traditional European systems using this Classic configuration are between 70 and 90 °C. In LTDH systems, the general conclusion is that it is not possible to utilise supply temperatures lower than 60–65 °C with this traditional network configuration. This limitation is linked to the need to safeguard installed hot water tanks and hot water circulation against Legionella growth, especially in extensive multi-family and service sector buildings.

Typical return temperatures in traditional systems using this Classic configuration are between 45 and 60 °C, since malfunctions appear in networks, substations, and customer heating systems. In LTDH systems without malfunctions, return temperatures as low as 30–35 °C can be obtained, since the necessary circulation flows containing the supply temperature are blended with the lower return temperatures from the substations. According to the inventory, lower return temperatures have not been identified in LTDH projects with this Classic configuration.

One major advantage of this configuration is that the components are commercially available since it represents the current, mainstream district heating technology. It is a well-known technology for established district heating providers, who often use it when they implement LTDH. Counteracting the Legionella bacteria with an appropriately high supply temperature is a major obstacle to obtaining lower supply temperatures with this configuration. The customer with the highest temperature demand also sets the

**Table 1**
Overview of the six main groups of network configurations and their main features.

| Configuration group | Network type for heat supply | Main features |
|---|---|---|
| Classic | Warm network | Two-pipe configuration used in most traditional district heating networks. |
| Modified Classic | Warm network | Three-pipe configuration that is a modification of the traditional Classic configuration to obtain the lowest possible supply and return temperatures in a warm network. |
| Multi-Level | Warm network | Multi-pipe configuration with at least two supply pipes that contain different temperatures. |
| Ultra-Low | Cold network | Two-pipe configuration that uses ultra-low supply temperatures for preheating customer heating systems that have additional heating devices. |
| Cold CHC | Cold network | Two-pipe configuration that uses the Ultra-Low configuration for heat deliveries, and the heat supply is mainly based on heat recovery from the condensers in decentralised chillers. Concurrently, cold deliveries (heat removals) are provided from the chiller evaporators. |
| Warm CHC | Warm network | Four-pipe configuration that uses a two-pipe Classic configuration for heat deliveries and a traditional two-pipe district cooling network for cold deliveries (heat removals) when the heat and cold supplies are jointly provided from centralised heat pumps. The condensers supply the heat to the district heating network, while the evaporators supply the cold to the district cooling network. |

temperature level for all customers since additional heating is normally not applied in the customer substations. Hence, the supplier has a responsibility to meet the temperature demands for all customers. Due to this supplier responsibility, customers with low temperature demands obtain no major benefits with this network configuration.

The suitability of this Classic configuration is linked to the use of conventional methods and components, but its economic benefit is hampered by its inability to reach really low temperatures in a warm network.

Implemented LTDH examples using the Classic configuration include Graz-Reininghaus since 2017 [13], Salzburg-Lehen since 2011 [14], Villach-Landskron since 2018 [15], Braunschweig-Rautheim since 2019 [16], Chemnitz-Brühl since 2016 [17], Crailsheim-Hirtenwiesen since 2008 [18], Freiburg-Gutleutmatten since 2021 [19], Munich-Ackermannbogen since 2007 [20], Wüstenrot-Weihenbronn since 2015 [21], Aarhus-Lystrup since 2010 [22], Lund-Brunnshög since 2019 [23], and Slough-Greenwatt Way since 2010 [7].

The **first variant** of the Classic configuration involves connecting a secondary network or a substation with a supply-to-supply connection, as shown in Fig. 2. The return pipes from these local networks or substations are reconnected to the supply pipe to avoid undesired temperature pollution of the return flow. Hence, this variant is suitable for connections that generate high return temperatures.

The main advantage of this cascading variant is a lower return temperature in the heat distribution network, but the connection requires a circulation pump in the service pipe to circulate the flow from the supply pipe. One major disadvantage is that the connection must be close to a major supply pipe servicing many substations beyond the supply-to-supply connection to redistribute the used flow. This variant is less suitable in the outskirts of the networks.

The Bromölla district heating network in Sweden recovers heat from a pulp and paper mill. The supply temperature is first delivered to a local industrial facility, and the return pipe from this local industry facility is then used as a supply pipe for the municipal district heating system [24]. Other examples of installations include absorption chillers that normally generate high return temperatures.

The **second variant** of the Classic configuration is to apply a return-to-return connection, as presented in Fig. 3. The return temperature from the network is used as the supply temperature for local networks or for substations that have low-temperature heat demands. Sometimes a third pipe from the supply pipe is used on occasions when the temperature demand is higher than the current return temperature in the network.

An advantage of this cascading variant is that it provides lower

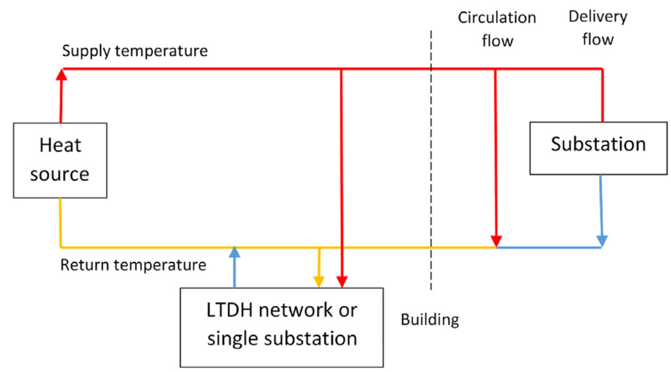


**Fig. 3.** Layout for the second variant of the Classic configuration in warm networks.

return temperatures in the heat distribution network, but it also requires a circulation pump in the service pipe from the return pipe. One major disadvantage is that the connection must be close to a major return pipe servicing many substations before the return-to-return connection. This variant is also less suitable in the outskirts of networks.

Examples include Hamburg-Wilhelmsburg, implemented in 2019 [25], and Höje Tåstrup-Sönderby, implemented in 2012 [26]. This configuration is further explored in the CASCADE project presented within Annex XIII of the IEA-DHC programme [27] and in Refs. [28,29].

### 3.2. Modified Classic configuration with warm networks

This second configuration group involves modifications of the traditional Classic configuration to obtain the lowest possible supply temperatures in a warm network without any additional heating in the connected buildings. The layout of the Modified Classic configuration is shown in Fig. 4. This configuration was developed by introducing three enhancements to the Classic configuration. First, the circulation and return flows are separated by a third pipe that takes care of the circulation flow, leading to lower return temperatures. Second, flat substations are used in multi-family buildings to avoid hot water circulation inside buildings, and hot water is always generated in heat exchangers to avoid hot water tanks. The Legionella risk is thereby reduced by avoiding the use of hot water circulation and hot water tanks in the buildings. This second enhancement enables the use of lower supply temperatures. Third, longer thermal lengths are used in the substation heat exchangers, enabling the use of lower supply temperatures.

This configuration was first presented in Ref. [30], while it was further explored and assessed in Refs. [31,32]. The circulation flow

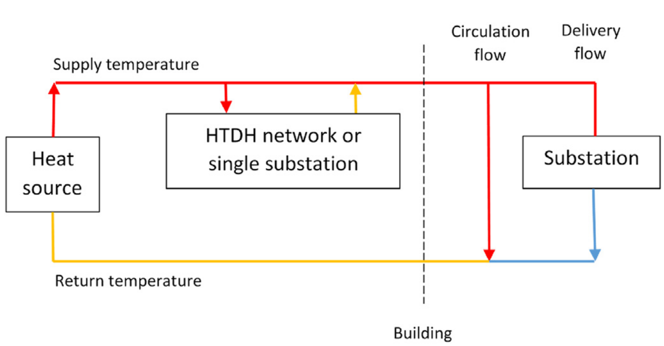


**Fig. 2.** Layout for the first variant of the Classic configuration in warm networks.

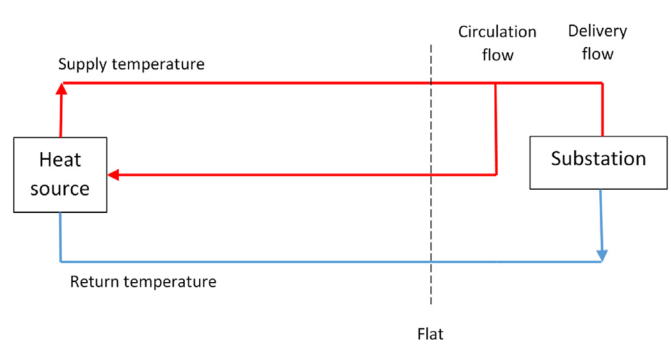


**Fig. 4.** Layout for the Modified Classic configuration in warm networks.

should be rather small, providing the opportunity to use a considerably smaller third pipe [33]. Expected network temperatures are 50–55 °C for the supply pipe and 20–25 for the return pipe.

The main advantage of this configuration is that the annual temperature levels will be about 10 °C lower than the lowest possible level in the Classic configuration. A disadvantage is that heat exchangers with longer thermal lengths and distribution pipes with triple pipe casings are not yet commercially available.

The suitability of this Modified Classic configuration is linked to the use of some unconventional methods and components, while its economic benefit is reinforced by its ability to reach really low temperatures in a warm network.

No implemented example exists yet for this configuration, but one small system is planned at Halmstad-Ranagård for commissioning in 2022–2023 [34].

### 3.3. Multi-Level configurations with warm networks

The third configuration group contains at least two supply pipes that have different supply temperatures. The general layout of this configuration is shown in Fig. 5. In this configuration, substations are connected between suitable temperature levels depending on the customer's temperature demands. One substation can be connected between high and medium temperatures, while another substation can be connected between medium and low temperatures; a third substation can be connected between high and low temperatures. Hence, the basic cascading principle is utilised, with the return flow from one substation providing the supply flow to another substation.

Advantages of this configuration are that provided supply temperatures are customised for each customer's temperature demand and lower return temperatures are obtained in the network compared to the those in the Classic configuration. The challenge is to provide the required flow at each supply temperature, which has to be addressed by a balancing function based on controlled circulation flows.

The suitability of this Multi-Level configuration is linked to its ability to deliver heat to both low- and high-temperature demands, while having both low- and high temperature heat sources.

The most pronounced Multi-Level network is the SEMHACH network, which has been supplying heat within three municipalities south of Paris (Chevilly-Larue, L'Hay-les-Roses, and Villejuif) since 1985. They apply three different supply temperatures from about 100 to 50 °C to their customers with one common return pipe having a temperature of about 30 °C, as described in Refs. [8,35]. By applying this Multi-Level network configuration, more heat can be extracted from existing geothermal boreholes.

The **first variant** of the Multi-Level configuration has one supply pipe for space heating and another supply pipe for the preparation of domestic hot water together with a common return pipe. Two examples of this variant are Naters-Reka Feriendorf, implemented in 2014 [36], and Paris-Clichy Batignolles, implemented in 2017 [37]. This first variant has also been used in the Berlin district heating systems for many years. The basic idea of using three pipe systems was originally implemented in Berlin when the Charlottenburg district heating system began in 1912 [38], and a similar choice was made when the Neukölln network was commissioned in 1920 [39].

The **second variant** uses a four-pipe system with two pipes for space heating and two pipes for generating domestic hot water. One example is Stuttgart-NeckarPark, implemented in 2020 [40].

A **third variant** of the Multi-Level network configuration applies different supply temperatures in different parts of the distribution network. The main goal is to reduce the demand for high temperatures in peripheral parts of the network. In Stockholm, a new residential area has been supplied with lower supply temperatures since 2017. The new area is located close to the major Värtan site, which has a surplus of an intermediate temperature coming from large-scale heat pumps and a flue gas condenser in a biomass CHP plant [41]. The equipment provider Grundfos has developed a standardised network shunt with a local circulation pump that manages to maintain a lower supply temperature for all customers located downstream of the shunt [42].

In some major European district heating networks, different supply temperatures have also been applied, similar to the use of high and low voltage in electricity distribution. In Vienna, heat distribution is divided between one large primary network using high supply temperatures and several hundred smaller secondary networks that use lower supply temperatures. In 2015, the total trench length of 1219 km was divided into two parts, with 54% for the primary network and 46% for the secondary networks [43]. In the Greater Copenhagen region, two transmission networks (CTR and VEKS) have applied higher supply temperatures since the 1980s while transferring heat to several local municipal heat distribution networks using lower supply temperatures [44].

### 3.4. Ultra-low configuration with cold networks

This fourth configuration group contains designs that use ultra-low supply temperatures for heat deliveries. The general configuration layout is shown in Fig. 6. The Ultra-Low configuration is based on the utilisation of heat sources with temperatures that are lower than traditional customer temperature demands. Instead of increasing the final supply temperature centrally, a lower temperature is distributed in the network. This lower temperature can be provided either by some central preheating or by using the original heat source temperature. Typical heat sources include sea, lake, ground, and mine waters together with low-temperature cooling waters from industrial processes or chillers. Applied supply

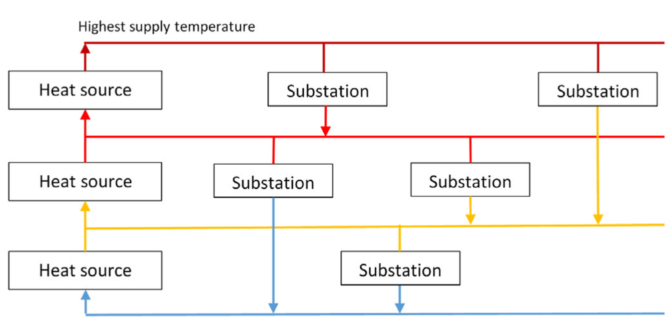


**Fig. 5.** Layout for the Multi-Level configuration in warm networks.

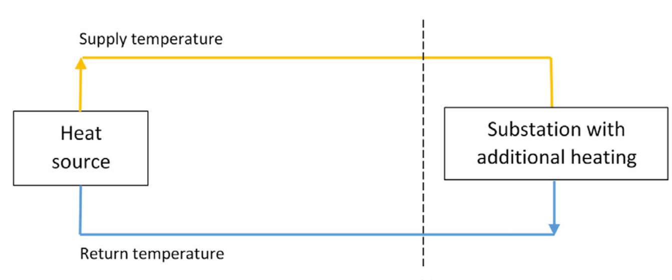


**Fig. 6.** Layout for the Ultra-Low configuration in cold networks.

temperatures in this configuration are 25–50 °C, while return temperatures range from 10 to 30 °C.

This configuration can be used for a wide range of distributed supply temperatures. If the distributed supply temperature is relatively low, additional heating in the buildings can be supplied by a heat pump using the heat distribution network as a heat source. If the distributed supply temperature is relatively high, a traditional electric hot water heater can be used for final heating of the domestic hot water, as the distributed supply temperature can be used to preheat the domestic hot water and meet the entire space heating demand using underfloor heating.

A major advantage of this configuration is that each customer is responsible for meeting their own temperature demands and must cover the cost of achieving these demands. Hence, the responsibility for the required temperature level, which falls on the supplier in the Classic configuration, is here transferred to the customer. Thus, customers with low-temperature demands obtain the full benefit of their lower temperature level. Further advantages include lower heat distribution losses in areas with low heat densities, and the fact that this configuration can be implemented everywhere, since ambient heat can always be used.

According to Ref. [45], the aggregated annual cost for many small heat pumps is currently higher than the corresponding cost for a central heat pump and a higher temperature level in the network. However, this economy of scale for larger units could disappear in the future, when small, standardised heat pumps can be manufactured in large volumes in industrial assembly plants similar to the manufacture of refrigerators and freezers. Another disadvantage is that the difference between the warm and cold temperatures is generally small in this configuration, leading to high flow demands and wider pipes. The electricity demand for pumping power thus becomes higher than for the traditional Classic configuration [46].

The suitability of this Ultra-Low configuration is linked to exploitation of heat sources having temperatures lower than the customer temperature demands, while passing on the responsibility to the customers for the temperature lift to reach their own temperature demands.

Examples of localities using Ultra-Low configurations include Leuven-Janseniushof since 2017 [47], Oberwald-Furka tunnel since 1991 [48], Bochum-Werne since 2012 [49], Hamburg-Eisenbahnverein Harburg since 2014 [50], Nümbrecht-Sohnius-Weide since 2017 [51], Wüstenrot-Agrothermie since 2012 [52], Aarhus-Geding since 2015 [53], and Hengelo-Akzo Nobel since 2015 [54]. Additional implemented cases using Ultra-Low configurations can be found in Refs. [55,56]. A monitored example for a small Italian system is presented in Ref. [57].

### 3.5. CHC configurations with cold networks

The fifth configuration group contains designs that utilise the CHC synergy by heat distribution in a cold network, such as that performed in the Ultra-Low configuration. The CHC synergy can also be applied in a warm network, which is the main feature in the next section of this chapter.

This CHC configuration takes advantage of the synergy of having both heating and cooling demands in the same area. The heat pump for heating extracts heat from the warm temperature through its evaporator and delivers a cold temperature, while the heat pump for cooling uses its condenser to increase the cold temperature to the warm temperature. In this way, the excess heat from cooling is used for heating, while the excess cold from heating is used for cooling. Hence, large buildings can also take advantage of the CHC synergy internally without connecting to district heating and cooling systems.

The general CHC configuration layout for cold networks is shown in Fig. 7. An important condition is that each decentralised connected device must have its own distribution pump. Flow demands for heating and cooling can be partly balanced directly within the distribution networks. During the winter when heating demands are high, the supply temperatures decrease and must be increased with an external heat supply. Inversely, during the summer when cooling demands are high, the supply temperatures increase and must be reduced by an external cold supply (heat removal). The short-term balance between heating and cooling can be managed by using the heat distribution network as short-term heat storage. The annual heat balance between heating and cooling can be managed with a large low-temperature aquifer or borehole heat storage. Applied warm temperatures in this configuration are 10–45 °C, while cold temperatures range from 5 to 25 °C.

The main advantage of this configuration is the exploitation of the CHC synergy. This configuration becomes more beneficial when cooling demands are high in comparison to heating demands. It also shares the advantages and disadvantages of the Ultra-Low configuration concerning responsibility for the temperature level, the economy of scale for large heat pumps, and higher flow demands due to small differences between warm and cold temperatures.

The suitability of this Cold CHC configuration is linked to its ability for exploitation of heat rejected from cooling processes, while passing on the responsibility to the customers for the temperature lift for their heating demands and the temperature reduction for the cooling demands.

Some implemented examples of the Cold CHC configuration with internal heat recovery are Paris-Saclay University since 2019, as described in Refs. [58,59], Lund-Medicon Village since 2018 [60], and London-LSBU since 2018 [61]. However, the LSBU system is planned for the CHC configuration, but has not yet utilised heat recovery from the chillers. One example of Cold CHC with external heat recovery is Zürich-FGZ, implemented in 2014 [62]. The external heat sources for this example are the cooling systems for two major data centres in the neighbourhood. Further implemented cases of Cold CHC can be found in Refs. [55,56].

Several variants are possible within this configuration group with cold networks, since the general design can utilise a wide range of distributed supply temperatures. The **first variant** is to apply a rather high ultra-low warm temperature for heating, similar to traditional district heating, as seen in Fig. 8. Hence, the responsibility for the temperature lift is taken by the heat pump for cooling.

With this design, heat delivery is possible without heat pumps for heating; instead, heat exchangers can be used for transferring heat to the low-temperature demands in the buildings. However, the condenser in the heat pump for cooling must be able to generate this higher level of warm temperature, reducing its energy efficiency. An implemented example that is close to this first variant

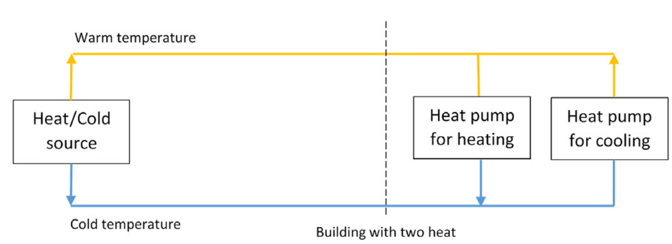


**Fig. 7.** Layout for the general CHC configuration in cold networks.

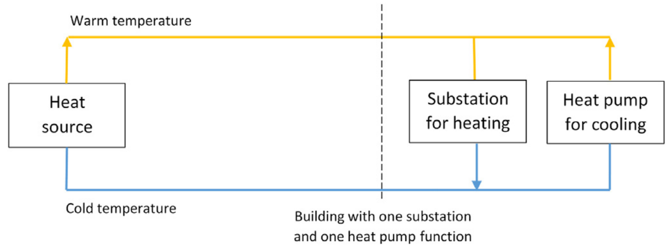


**Fig. 8.** Layout for the first variant of the CHC configuration in cold networks.

is the Zürich-FGZ system that was mentioned earlier as a general example of Cold CHC, since rather high intermediate temperatures (24–28 °C) are sometimes applied between the two low-temperature heat sources and the decentralised heat pumps in the building clusters.

A **second variant** is possible when relatively low warm temperatures exist, as seen in Fig. 9. This design leads to low cold temperatures, creating the opportunity to connect cooling substations directly to the cold pipe. Hence, typical network temperatures will be close to the temperatures applied in ordinary district cooling networks, such as 6 °C for the cold side and 16 °C for the warm side. The responsibility for the temperature lift for heating is taken by the heat pump. This solution can also be accomplished in ordinary district cooling systems when the return flow is utilised as a heat source for heat pumps.

Implemented examples of this second variant include Vienna-Krieau since 2010 [63], Geneva-GLN since 2008 [64,65], which will be extended ten times into the GeniLac system [66], Rotkreutz-Suurstoffi since 2010 [67,68], Visp-West since 2007 [69], Zürich-ETH since 2013 [70], and the Bergen-Sydnes campus area since 1995 [71].

A **third variant** contains neither specific warm nor cold pipes. Instead, all buildings are connected to the same pipe that contains a constant circulation flow in an integrated loop with intermediate temperature. All heat pumps for heating extract heat from the network, while all heat pumps for cooling add heat to the network. This configuration variant can also be balanced with external heat and cold supplies, as well as with thermal storages. For example, Zinal implemented such a one-pipe system in 2017 [72], having a network temperature between 0 and 10 °C during a year. These systems are also called reservoir networks [73].

### 3.6. CHC configuration with warm network

The general configuration layout for the CHC configuration together with a warm network for heating is shown in Fig. 10. Centralised heat pumps deliver heat to the district heating network and cold to the district cooling network. The configuration is based on centralised single heat pumps that are powerful enough to generate high supply temperatures for traditional district heating

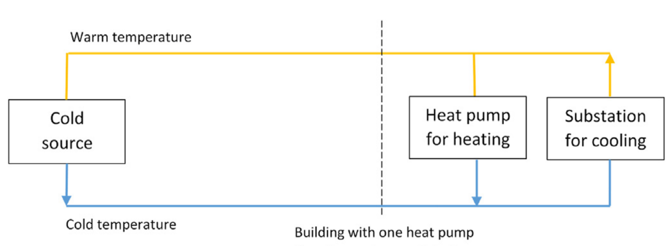


**Fig. 9.** Layout for the second variant of the CHC configuration in cold networks.

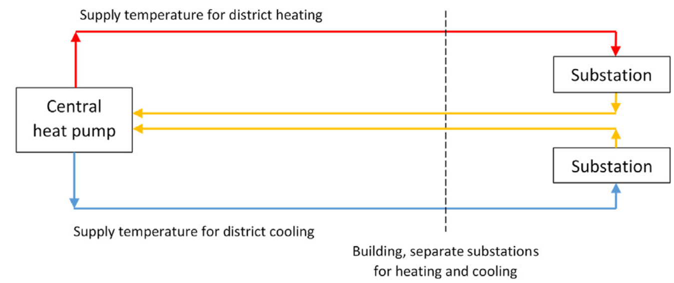


**Fig. 10.** Layout for the CHC configuration in warm networks.

systems and low supply temperatures for traditional district cooling systems simultaneously. The heat is supplied from the heat pump condensers, while the cold is supplied from the heat pump evaporators. The short-term balance between heating and cooling can be managed by separate heat and cold storage facilities.

One advantage of this configuration is that it can be used in conjunction with existing district heating systems. A disadvantage is that the heat pumps must be able to manage the entire temperature lift from the district cooling system to the district heating system. Moreover, this high temperature lift will require more electricity for the compressor in the heat pump, resulting in lower energy efficiency.

The suitability of this Warm CHC configuration is linked to its ability for exploitation of heat rejected from cooling demands, while taking full responsibility for meeting the customer temperature demands for both heating and cooling.

One typical example of Warm CHC is Stanford University, which implemented this system in 2015 [74,75]. This CHC synergy in warm networks has also been implemented in some Swedish district heating systems that also operate district cooling systems, including Stockholm. In 2019, one fifth of the cold input to all Swedish district cooling systems came from cold supplies using this configuration [76]. In Helsinki, the Katri Vala underground heat pump plant utilises heat from both the district cooling system and the purified sewage water system, while simultaneously providing cold to the district cooling system [77]. It was initially commissioned in 2006, but with the latest extension to be finalised in 2023, the output will be 155 MW heat and 103.5 MW cold with an input of 51.5 MW electricity [78].

### 3.7. Summary of findings

In this section, more aggregated information is provided about the LTDH network initiatives that were identified in the inventory with respect to the six main network configuration groups.

In Fig. 11, the numbers of network configurations are presented by configuration group and case status in 2020 for all identified cases. As seen in the figure, the Classic configuration was chosen for 45% of cases, while an additional 11% of cases were associated with the three other network configurations that use warm networks. Cold networks were preferred in 41% of all cases, which use the Ultra-Low or Cold CHC configurations. In the remaining 3% of cases, it was not possible to identify the network configuration due to insufficient case information.

In Fig. 12, the numbers of implemented network configurations are presented by configuration group and affiliation to operator group. It can be concluded that the Classic configuration is preferred by district heating operators, since 62% of their LTDH initiatives were based on this network configuration. Only 21% of cases initiated by other operators made the same choice, since 73% of these initiatives were based on cold networks, using the Ultra-

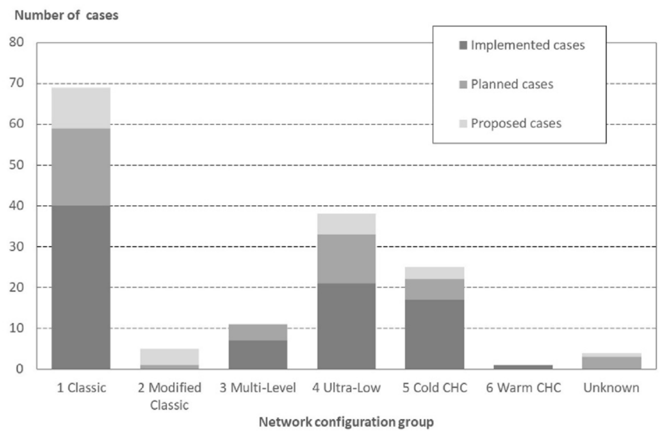


**Fig. 11.** The number of identified LTDH networks with respect to main network configuration group and the 2020 status concerning implemented, planned, and proposed cases.

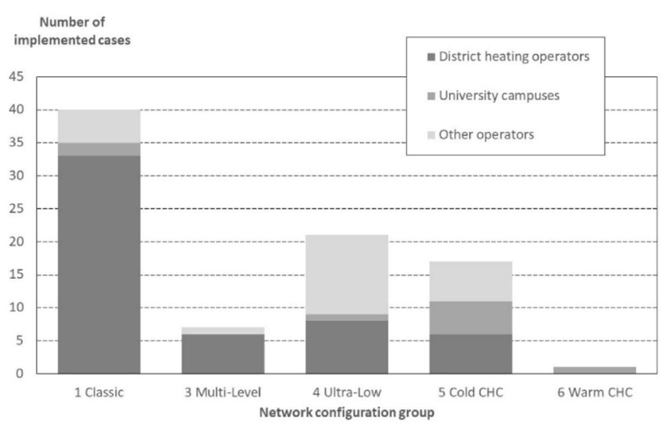


**Fig. 12.** The number of identified implemented LTDH networks with respect to main network configuration group and three different groups of operators.

Low or Cold CHC configurations. This reveals a strong path dependence for district heating operators, while other operators were more open to new technological options.

## 4. Discussion

As a first reflection, the inventory provided enough inputs to identify the main trends and several examples of implemented network configurations concerning LTDH. However, it is too early to assess the specific competitiveness of each network configuration, since most new network configurations are not yet fully developed, as they are early in their developing and learning processes. More detailed assessments will also be required for analysing the initial operating experiences from the new network configurations.

The second reflection is that further network configurations will probably be used in the future, especially through the creation of hybrids between the different configurations that have been presented in this paper. A possible direction might be the use of heat pumps for those customers with the highest temperature demands in existing high-temperature networks based on the traditional Classic configuration, making it possible to reduce the general temperature level in existing systems. A more extreme example is the HIGHLIFT project aiming to generate steam using a heat pump by extracting heat from a traditional district heating system [79].

Third, exploitation of the CHC synergy has emerged as the fundamental idea for the CHC configurations, both for cold and warm networks. This synergy will certainly become a substitute in many future DHC systems for the currently used CHP synergy. Two vital conditions for the competitiveness of the CHC configurations are that both heating and cooling should appear simultaneously with a high proportion, and that the magnitude of the cooling demand is high compared to the heating demand. Future assessments will also have to provide more information about the choice between heat distribution in cold or warm networks when exploiting the CHC synergy.

Fourth, several university campus systems appeared as forerunners in the inventory of low-temperature initiatives [1] by using new kinds of network configurations. In these cases, the universities' own campus systems have been used as testing areas for LTDH. These networks have also become suitable and active living labs for students, giving them direct access to the future DHC technologies to be used during their upcoming professional careers. Campus examples concerning LTDH appear in Canada (Ontario Tech in Oshawa), France (Saclay University located southwest of Paris), Germany (Technical University of Darmstadt), the Netherlands (Technical University of Delft), Norway (Bergen University), Switzerland (ETH in Zürich), the United Kingdom (London South Bank University), and the USA (Stanford University).

## 5. Conclusions

First, six main network configuration groups were identified from the inventory of the 153 identified early LTDH network initiatives. An additional eight variants were identified for the Classic, Multi-Level, and Cold CHC configurations, giving a total of fourteen possible network configurations for LTDH.

Second, the main feature of LTDH became the division into heat distribution with cold or warm networks. Cold networks are used for the Ultra-Low and Cold CHC configurations, while the remaining four configurations are used in warm networks. If heat is available at a temperature higher than the customer's temperature demands, warm networks are preferred. If the heat sources have supply temperatures below the customer's highest temperature demands, cold networks with the Ultra-Low configuration might be a competitive option. The supplier takes full responsibility for reaching the customer's temperature demands in warm networks, while this is the customer's responsibility in cold networks. Therefore, customers with low-temperature demands are more highly rewarded in cold networks than in warm networks.

Third, the suitability of each network configuration depends on the local conditions in each location and how their merits and drawbacks are assessed. The most decisive condition will be the temperature of the heat sources to be used. The Classic configuration is linked to the use of conventional methods and components, but its economic benefit is hampered by its inability to reach really low temperatures in a warm network in order to harvest low-temperature heat sources without using heat pumps. The Modified Classic configuration is linked to the use of some unconventional methods and components, while its economic benefit is reinforced by its ability to reach really low temperatures in a warm network. The Multi-Level configuration is linked to its ability to deliver heat to both low- and high-temperature demands, while having both low- and high temperature heat sources. The Ultra-Low configuration is linked to exploitation of heat sources having temperatures lower than the customer temperature demands, while passing on the responsibility to the customers for the temperature lift to reach their own temperature demands. The two CHC configurations exploit the CHC synergy. But the Cold CHC configuration do not take the responsibility for the final temperature adjustments for meeting the customer temperature demands for heating and cooling, while the Warm CHC takes this responsibility.

## Credit author statement

The corresponding author is the sole author of this paper and has performed all stages to reach the final stage of a printable manuscript.

## Declaration of competing interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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