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Double Loop Network for Combined Heating and Cooling in Low Heat Density Areas

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Abstract: This study investigated a double loop network operated with ultra-low supply/return temperatures of 45/25 °C as a novel solution for low heat-density areas in Denmark and compared the proposed concept with a typical tree network and with individual heat pumps to each end-users rather than district networks. It is a pump-driven system, where the separate circulation of supply and return flow increased the flexibility of the system to integrate and displace heating and cooling energy along the network. Despite the increased use of central and local water pumps to operate and control the system, the simulated overall pump energy consumption was 0.9% of the total energy consumption. This was also an advantage at the design stage as the larger pressure gradient, up to 570 Pa/m, allowed minimal pipe diameters. In addition, the authors proposed the installation of electrically heated vacuum-insulated micro tanks of 10 L on the primary side of each building substation as a supplementary heating solution to meet the comfort and hygiene requirements for domestic hot water (DHW). This, combined with supply water circulation in the loop network, served as a technical solution to remove the need for bypass valves during summer periods with no load in the network. The proposed double loop system reduced distribution heat losses from 19% to 12% of the total energy consumption and decreased average return temperatures from 33 °C to 23 °C compared to the tree network. While excess heat recovery can be limited due to hydraulic issues in tree networks, the study investigated the double loop concept for scenarios with heat source temperatures of 30 °C and 45 °C. The double loop network was cost-competitive when considering the required capital and operating costs. Furthermore, district networks outperformed individual heat pump solutions for low-heat density areas when waste heat was available locally. Finally, although few in Denmark envisage residential cooling as a priority, this study investigated the potential of embedding heating and cooling in the same infrastructure. It found that the return line could deliver cold water to the end-users and that the maximum cooling power was 1.4 kW to each end-user, which corresponded to 47% of the total peak heat demand used to dimension the double loop network.

Keywords: double loop network; district heating; district cooling; ultra-low temperatures; power-to-heat

1. Introduction

The building sector is responsible for 40% of the total energy demand in Europe [1] and as part of the Energy Efficiency Directive (EED 2018) and Energy Performance of Buildings Directive (EPBD) [2,3], the mitigation of greenhouse gas emissions and the reduction of energy consumption from buildings must be a cornerstone of every climate change strategy in the member states. Among other solutions, district heating and cooling (DHC) is recognized as one of the key technologies in the transition towards a fossil-fuel-free energy system. The competitiveness of DHC has been related to the capacity of using low-grade or renewable energy sources—e.g., heat recovery from CHP or deep-water cooling from seas or lakes. This ensures the security of supply, higher flexibility, and competitive energy prices compared to individual heating and cooling solutions [4,5]. The technological challenge, considering the future fossil-fuel-free energy system, is that the DHC infrastructure needs to be integrated with the electricity grid and transportation sector to efficiently exploit local energy sources and to further increase the flexibility and security of the energy supply due to the intermittent nature of renewable sources [6]. Hence, the DHC technology is in a transition process towards the 4th generation district heating (4GDH) concept, where average supply and return temperatures in the range of 55–60 °C and 25–30 °C are expected to be adequate to fulfill the space heating (SH) and domestic hot water (DHW) requirements even for existing buildings [7–10]. In fact, lower temperatures are crucial to allow better exploitation of renewable and local waste heat sources and to improve the coefficient of performance (COP) of heat pumps [11–15]. Although the demand for cooling is larger on a global scale compared to heating, district cooling (DC) has a limited market share in Europe, covering only 1.3% of the total cooling demand. Furthermore, room air-conditioners and central air-conditioners are the dominant cooling devices currently in use [5,14,16]. However, the Copenhagen DC network showed the possibility to reduce the energy consumption and CO_2 emissions by 40% and 70% respectively compared to a scenario using air-conditioners, and it is expected that DC will be fast-growing in both temperate and warm climate countries in the coming years [17,18].

1.1. State of the Art and Future Challenges

The level of urbanization is expected to grow in Europe in the coming years and 84% of the population will be living in urban areas by 2050 [19]. Similar trends will be experienced in Denmark, and the municipality of Copenhagen foresees a 14% increase in population between 2016 and 2025 with 2.8 million m^2 of new office, commercial, cultural, and educational spaces [20]. The new buildings, designed under stringent building regulations, will be characterized by low energy demand. This new situation will call into question the attractiveness of DHC, technically and economically, as establishing new networks in low linear heat density areas may reduce their competitiveness with respect to individual energy solutions—e.g., heat pumps [21–23]. Hence, new technical solutions are required to sustain the DHC competitiveness in new urban areas and face the novel challenges that will arise in the future energy markets.

1.1.1. Reduction of Distribution Losses and Implementation of Ultra-Low-Temperature

As the energy performance of buildings improves, the relative share of heat distribution losses increases, which affects the profitability of DHC networks. Hence, operating DH networks with ultra-low supply temperatures in the range of 30–45 °C would ensure a reduction in distribution heat losses and higher utilization of renewable and local waste heat sources. This would not compromise the indoor comfort for the end-users because the new SH systems would be designed for low temperatures.

1.1.2. DHW Preparation without Any Risk of Legionella

According to Danish standard DS 439 [24], instantaneous DHW preparation requires 50 °C, or 55 °C if DHW recirculation is in place, and 60 °C in hot water storage tanks to avoid risks related to Legionnaires' disease. To operate the networks with temperatures lower than 55 °C, new solutions using electricity can be implemented to boost the supply temperature and safely deliver DHW to the end-users [25–28]. The optimal use of electricity and heat boosting devices can be one of the coupling points for the future integrated energy system.

1.1.3. Improved Design for Supply Heat during Summer and No-Load Periods

Thermostatically controlled street and sub-station bypass valves are the state of the art solution in DH networks to guarantee the required supply temperature to deliver DHW during no-load periods, particularly in summer for the peripheral areas of the network [4]. However, these have the negative effect of increasing the average return temperatures in the networks. Averfalk and Werner proposed an innovative solution for new residential areas using a three-pipe distribution network, where the bypass flows can be recirculated in the supply line rather than contaminating the return line [29,30], although this will require an extra pipe. Instead, Brand et al. proposed the "comfort bathroom" concept, where the bypass flow heats the bathroom floor and provides comfort when there is no demand for heating otherwise [31]. Hence, a new design for the distribution network can play an important role in reducing the impact of bypass flows in DH networks.

1.1.4. Improved Distribution Network

The typical branched or tree network configuration is operated centrally and the distribution flows in one direction. Integrating distributed energy sources helps transition the network towards a system relying on renewable and local excess sources for heating or cooling. The type of connection and control labeled return-supply (R/S) heats water from the return line before inserting it into the supply line. The type labeled return-return (R/R) reinserts heated water back into the return line. These types of connections for decentralized renewable heat sources or "prosumers" were investigated in Refs. [32–36]. The R/S connection is generally preferred if the local heat source can deliver the feed-in flow at the right temperature to the supply line. Otherwise, the R/R connection is used, although this has the drawback of increasing return temperatures in the network. Nonetheless, the control of the decentralized heat sources in the typical tree network can be challenging due to the varying pressure level generated by the feed-in flow [36,37]. This can limit the deliverable energy into the network. Kuosa et al. proposed an alternative pump-driven ring or loop network for low-density areas, where controlling valves are replaced by pumps on the primary and secondary sides. This led to an even distribution of pressure differences, which made the hydraulics of the system more accurate and controllable and provided better cooling of the supply flows compared to traditional tree network layout [38,39]. Generally, a higher pressure head reduces the size of pipes at the design stage and, as a consequence, decreases the distribution of heat losses and costs. Tol et al. investigated an optimization method that improved the design of DH pipelines based on the simultaneity factor of the heat load for low-temperature networks in Denmark. They compared tree and loop networks, the use of boosting pumps, and the impact of boosting the supply temperature during peaks and concluded that they can both lead to reduced pipe dimensions [40–42].

1.1.5. Integration of Heating, Cooling, and Electricity

Several publications introduce the novel concept of 5th generation district heating and cooling (5GDHC) as networks with temperatures similar to the ground temperature that are connected to decentralized substations with heat pumps (HPs) to cover heating and cooling with the same infrastructure. Buffa et al. provided a comprehensive description of the concept and a survey of on-going projects, highlighting the main advantages: to ease the integration of local excess heat and renewable sources due to the neutral temperature in the networks; the bi-directionality to deliver heating and cooling throughout the entire year according to the customers' needs using substations with HPs; the minimization of distribution heat losses [43,44]. The 5GDHC concept was also the focus of the European project FLEXYNET [45]. The project documented the aforementioned advantages, but under the current market conditions, they did not manage to offset the increased pumping costs due to smaller temperature difference (ΔT), the increased electricity consumption for the decentralized HPs operation and the higher capital costs of the end-users' substations [46]. Furthermore, there is a knowledge gap regarding the technical and economical effectiveness of DHC networks in future integrated energy systems based on local renewable and excess sources for heating and cooling in new urban areas.

1.2. Aim and Novelty of the Investigation

The scope of this article is to illustrate a double loop network as a novel technical solution for new urban areas characterized by low linear heat density. The investigation focused on addressing the main challenges for the design and operation of the loop network and aimed to evaluate, technically and economically, the integration of multiple local energy sources and the possibility of using the return lines for collecting low-temperature excess heat and delivering cooling in a new urban area.

2. Double Loop Network

2.1. General Concept Description

This Section presents the double loop concept and the main proposed technical solutions. The core ideas were the high flexibility to integrate local heat sources and the potential to cover both the heating and cooling demand using the same infrastructure. As presented in the schematics of Figure 1, two main loops—one for supply and one for return—collect, circulate and displace heating and cooling in the area. Decentralized energy sources connect to the main loops and deliver heating and cooling in the network. The system is pump-driven and local agents—either end-users or de-centralized energy sources—are hydraulically separate from the main loop by the use of local pumps.

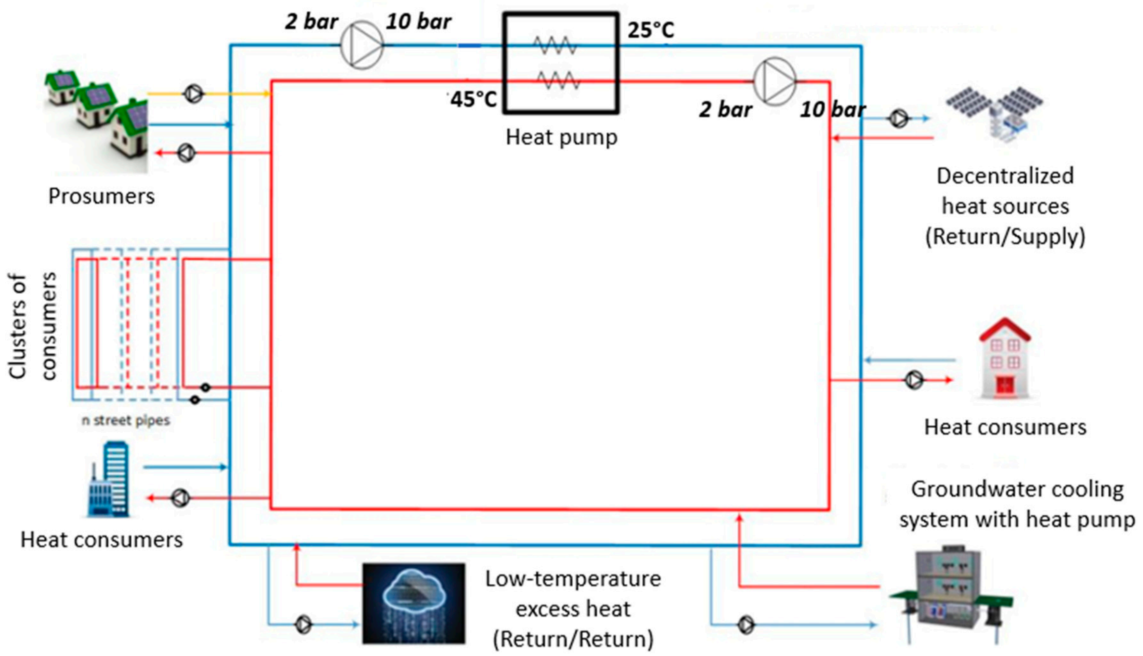

Figure 1. General schematics for the double loop concept.

2.2. The Role of the Main Pumps

The two main pumps, installed in the main supply and return loops as in Figure 1, have the role of adjusting the circulating flows to displace heating and cooling potential while maintaining the required differential pressure and optimal temperature level in the network. The key element is that the main pumps only regulate the flow in the main loops, as the local pumps control the local hydraulic conditions of the agents. The main pumps must always secure a water flow in the forward direction in all pipe segments of the main loops. This is necessary to avoid situations of counterflow or insufficient flow, which could be detrimental to the operation of the various connected agents. To guarantee the minimum forward flow throughout the entire system, flow meters monitor the local flows in each segment of the loops. If a local heat producer starts pumping water from the return loop, the local flow conditions in the main loops will change. The flow meter associated with the heat producer will send signals to the main pumps, which will adjust their speed to maintain the local flows above the minimum threshold. To save cost, the local flow in each pipe segment will be obtained from a mass balance of flows from energy meters on all connections to the main loops. The installation of a local flow meter will hence be a prerequisite for the connection of an agent to the main loop, regardless of whether it is for the production or consumption of heating and cooling.

2.3. Local Pumps

Local pumps operate to extract and/or distribute energy to the various agents connected to the double loop (i.e., suppliers, consumers and/or prosumers), and in this way, separate the local hydraulic conditions from the main loops. An advantage is that the local pumps ensure a higher pressure head than if there were no local pumps, which minimizes the necessary size of the pipes at the design stage. The local pumps adapt their speed according to the specific needs of the agents without affecting the authority of the main pumps in the double loop. This simplifies and increases the robustness of the connection of the decentralized energy sources and end-users to the main network.

2.4. Connection of Clusters of Houses to the Main Loop

Each cluster is composed of several houses that are hydraulically coupled along street pipes, as presented in Figure 2. Each cluster has three local pumps: one in the supply line and two in the return line. They regulate the water flow in the cluster according to the demand. The pump in the supply line ensures the necessary flow to cover the demand for heating. The pump in the return line at the end of the cluster sends the water flow back to the main return loop at the specific pressure corresponding to the location of the cluster in the double loop. The pump in the return line at the beginning of the cluster has the responsibility to extract the flow from the main return loop to cover the cooling demand during summer. In the case of no residential cooling demand, this pump is not necessary.

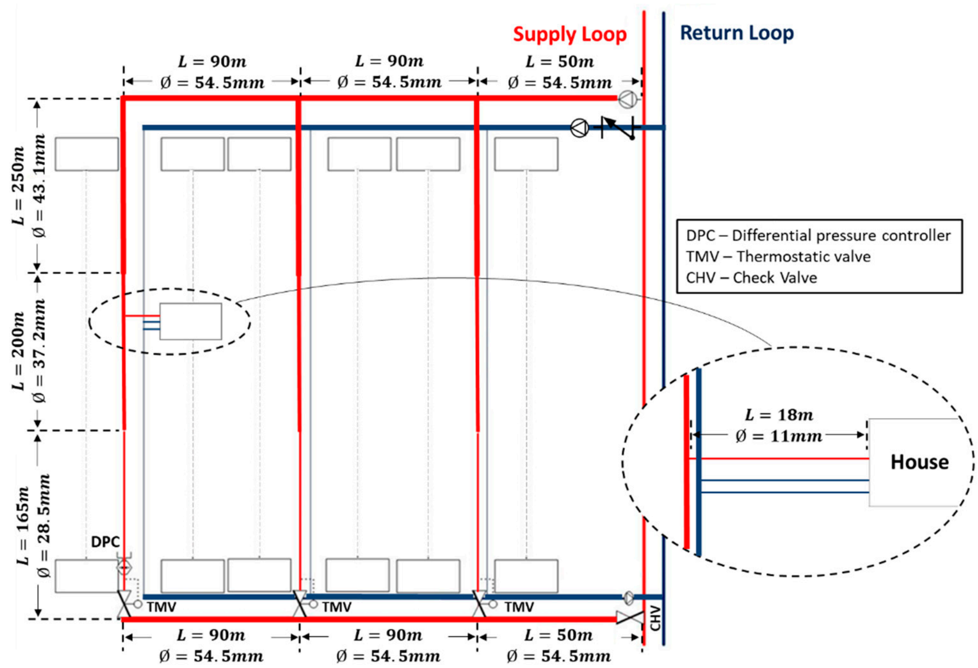

Figure 2. Connection of cluster of 150 houses to the main loops.

The novelty of the concept is that during no-load periods especially in summer, due to the looped layout, the supply lines can circulate the necessary flow to keep the pipes sufficiently warm. This is enabled by thermostatically controlled valves installed at the end of each street pipe that open if the temperature is below the set-point. Hence, this summer circulation flow returns to the supply line, which negates the need for bypass valves in the cluster and avoids temperature increases in the return line. In addition, a differential pressure controller, installed at the critical user, always guarantees the minimum differential pressure and ensures enough flow in all conditions. Finally, a check valve at the end of the cluster prevents back-flow from the main loop during winter operation and only opens when there is summer circulation flow in the cluster. To this extent, the pump in the cluster's supply line has to compensate for local pressure loss and ensure the necessary positive pressure to return the flow to the main supply loop according to the cluster's specific location and pressure level in the double loop.

2.5. End-Users' Substations and Connection to the Network

The substation schematics and the connection of each house to the network are presented in Figure 3. The double loop is expected to be operated with ultra-low supply temperatures in the range of 30 °C to 45 °C. These temperature levels are suitable to guarantee SH comfort in new or energy-refurbished Danish buildings equipped with floor heating systems or low-temperature radiators. However, a temperature of 50 °C is mandatory within 10 s for instantaneous DHW preparation according to the Danish Standard DS 439 [24] to avoid any risk of legionella proliferation in the DHW circuit. Based on the design draw-off program, a peak demand of 32.3 kW must be ensured to fulfill the requirement for a shower and kitchen-use with tapping lengths of 5 and 2.5 min, respectively, where the interval between two draw-offs is 20 min.

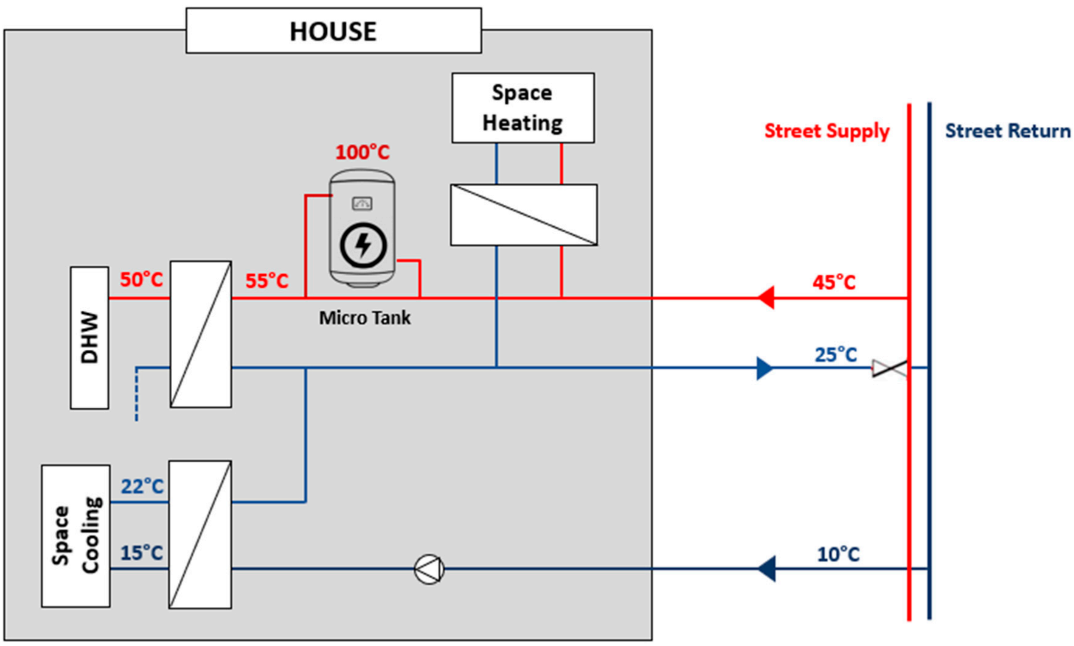

Figure 3. End-users' substation schematics.

Hence, a small vacuum insulated tank with an electrical heater is integrated into the proposed substation to safely deliver DHW. The tank stores a few liters of water, which an electric heater heats up to boiling temperature (100 °C). When a draw-off starts, the water in the service supply line mixes with the water from the micro tank to achieve 55 °C on the primary side and 50 °C on the secondary side of the DHW heat exchanger, as illustrated by Figure 3. The use of the micro tank also makes it possible to close the service pipes when there is no heat demand in summer. When DHW is initially drawn-off, the substation uses a greater share of hot water from the micro tank to compensate for cooler temperatures in the service pipe until the supply water flow at 45 °C reaches the substation. The possibility to close service pipes reduces the distribution of heat losses. As illustrated in Figure 3, the service pipe comprises three pipes. In the proposed connection, the third pipe, with the aid of a small pump, can be used to extract flow from the return line and cover the cooling demand. The heated flow is sent back to the return line. If cooling will not be delivered to residential users, a typical twin-pipe service pipe can be used. A similar arrangement for the supply line was proposed by Averfalk and Werner in Refs. [29,30] to allow the recirculation of the supply hot water and avoid return temperature contamination in a typical tree network layout.

2.6. Connection of Decentralized Energy Sources

Based on an existing project in Bjerringbro in Denmark [47], Figure 4 illustrates a combined energy system where groundwater provides a free cooling source to cover local demand during summer while storing the excess heat in an aquifer. During winter, a heat pump cools the groundwater while delivering heat in the main supply loop at the optimal temperature, so that the aquifer maintains an optimal temperature for both summer and winter operation. Similarly, other decentralized heat sources—i.e., solar fields, excess heat from data centers, supermarkets, etc.—can be connected to the main loop using R/S or R/R connections according to the achievable temperature from the specific source. Local pumps and mixing shunts provide control of the temperature and pressure. A solution without heat exchangers may be preferred to reduce pressure losses and increase the operational flexibility of the system.

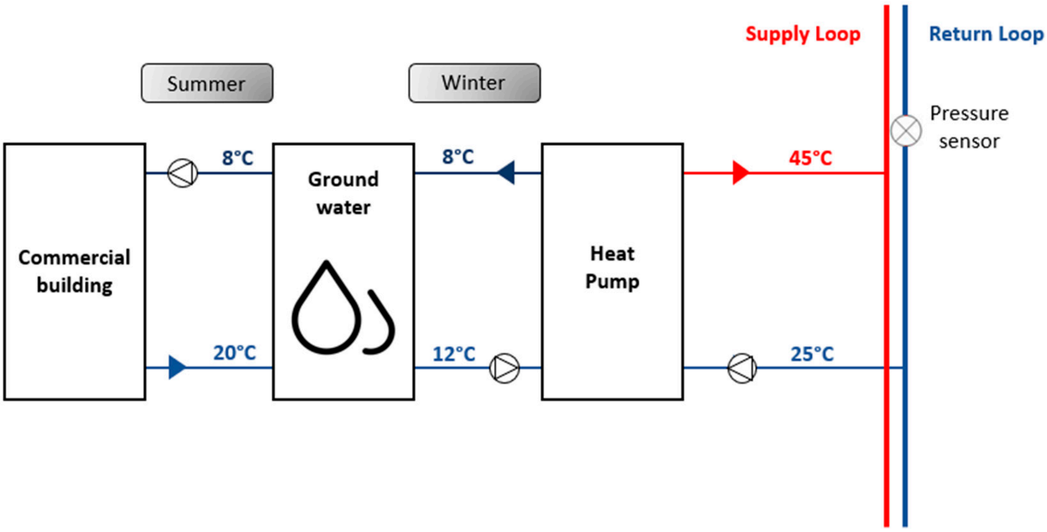

Figure 4. Schematics of the connection of groundwater heating and cooling system to the double loop network.

2.7. Assumptions

The investigation used several significant assumptions. The systems operated under ideal conditions without considering errors in either the primary or secondary system. The electricity price was fixed. Furthermore, the investigation assessed the possibility to deliver residential cooling using the return line of the double loop concept, even though active cooling is not currently a priority in Denmark.

3. Methods and Data

This section describes the methods used for the network design and defines the key performance indicators to assess the effectiveness of the proposed technical solutions.

3.1. Network Design and Operation

3.1.1. Design Load for the Network

Danish buildings are typically heating dominated, and typically only commercial buildings use active cooling due to the strong local potential for natural ventilative cooling. Hence, the authors based the network design on the peak heating demand. Firstly, the authors assumed a peak SH demand of 15 W/m^2 for low energy buildings based on calculation methods from the Danish standard DS 418 [48]. This considers the building envelope and ventilation heat losses at a winter design temperature of −12 °C and no internal heat gains. The peak demand for instantaneous DHW preparation for an individual building is 32.3 kW according to the DS 439 [24], but for multiple buildings, a simultaneity factor must be taken into account. This considers the probability that multiple DHW draw-offs occur at the same time and prevents oversized systems. Hence, given n as the number of dwellings connected to the DH network, the DHW demand (kW) is calculated with Equation (1) [24]:

$$Q_{DHW} = 1.19 \times n + 18.8 \times n^{0.5} + 17.6 \quad (1)$$

The total design heat load to size the network was based on the maximum value between SH and DHW in each Section of the network. In the event of concurrent SH and DHW demand, the end-user's substations prioritize DHW, and the SH system switches off. As the DHW draw-offs typically last only a few minutes, this does not affect the end-users' indoor comfort [49].

3.1.2. Design Mass Flow Rate and Pipe Dimensioning

The water flow rate $\dot{m}$ required to cover the design heat load in each segment of the heating network was determined with Equation (2):

$$\dot{m} = \frac{max(Q_{SH}; Q_{DHW})}{c_p \cdot \Delta T} \quad (2)$$

where ΔT represents the temperature difference between supply and return lines and c_p is the water-specific heat capacity. Given the length of the pipes L and the total pressure drop ΔP in the main loops and the clusters/local areas of the network, the Darcy–Weisbach equation may be used to determine the required diameters D for Section of each pipe before selecting suitable pipes from product lists. Equation (3) shows the reformulated Darcy–Weisbach equation:

$$\frac{\Delta P}{L} = \frac{8\lambda}{D^5 \pi^2 \rho} \times \dot{m}^2 \quad (3)$$

where λ is the friction factor and ρ is the water density. To estimate the friction factor λ as a function of the pipe characteristics (diameter D and pipe roughness ε) and flow regime (Reynolds number Re), the Colebrook–White equation required an iterative solution of Equation (4).

$$\frac{1}{\sqrt{\lambda}} = -2log\left(\frac{\frac{\varepsilon}{D}}{3.71} + \frac{2.51}{Re\sqrt{\lambda}}\right) \quad (4)$$

3.1.3. Network Annual Energy Consumption

Using calculation methods from the Danish standard DS 418, the assumed yearly energy consumption for SH and DHW in new low energy buildings was 17 and 13 kWh/m^2/year, respectively [48]. Dynamic simulations of both the residential and commercial buildings were performed with the software Polysun [50], ensuring to fulfill the requirements of the yearly energy consumption. Then, the duration curve was defined by adding the profiles for each type of building connected to the DHC network. Even if the local DHW usage presents typical patterns with peaks in the morning and the evening according to the different building destinations [51,52], the total daily DHW energy consumption for the entire urban area gets fairly constant throughout the year [4]. Small differences typically occur during summer in relation to holiday periods. In addition, the DHW demand is considered only for a residential building with no consumption during night-time. The load profile considers the local weather conditions for Denmark. No cooling energy demand was considered for the residential buildings, whereas based on the results of the EU funded project STRATEGO, an active cooling consumption of 30 kWh/m^2/year was assumed for commercial buildings in Denmark [16,53].

3.1.4. Optimization of Summer Circulation Flow

One of the key innovations of the proposed concept is the possibility to circulate both the supply and the return flows separately, which avoids return temperature contamination due to otherwise necessary bypass flows. Hence, when there is no heat demand, the flow in the supply lines needs to compensate for supply temperature degradation and maintain the minimum specified temperature everywhere in the network. The optimal flow was determined by minimizing the cost of the heating required to compensate for the distribution of heat losses and the pumping energy for the summer circulation flow. The pump electrical power P_{el_pump} and distribution heat losses Q_{heat_loss} were calculated using the following equations:

$$P_{el\_pump} = \frac{\dot{m} \cdot \Delta P}{\eta} \tag{5}$$

$$Q_{heat\_loss} = \sum_{i}^{n} U_i \cdot L_i \tag{6}$$

where $\dot{m}$ is the circulation flow to compensate for the distribution heat losses during summer and calculated using Equation (1); ΔP is the pressure loss calculated for the specific flow in the network; η is the overall efficiency of the pump, which was assumed to be 0.8; U_i is the heat loss per unit of length as calculated from the pipe manufacturer's catalog considering the fluid and ground temperatures and the ground thermal conductivity; L_i is the specific pipe length. To obtain the pump energy and distribution heat losses, Equations (5) and (6) need to be integrated over time.

3.1.5. Capital and Operating Costs

The focus of the article was to assess the economic feasibility and competitiveness of the double loop network for a low heat density area in the market situation where there is strong integration between electricity and heating as well as the possibility to collect local decentralized heating or cooling sources. To obtain a fair cost comparison, the proposed concept was compared with the typical tree network layout and end-users individual heat pumps. The technological data as well as the capital and operating costs were derived from the Danish Energy Agency catalog for individual and district heating solutions [54,55], as Table 1 summarizes.

Table 1. Capital and operating costs for heat pumps.

		Residential House	Commercial Building	Large ASHP	Large WSHP Heat Source at 12 °C	Large WSHP Heat Source at 30 °C
Yearly COP	-	3.2	3.8	4.1	4.6	6.2
Investment	k€/kW	3.33	1.11	1.06	1.30	1.14
Fixed O&M	€/kW/year	-	-	2	2	2
Variable O&M	€/kWh	0.090	0.080	0.073	0.066	0.049
Lifetime	year	18	18	25	25	25

The total linear average price for the network, including the capital and installation costs for pipes in a new development area, was 270 €/m for the double loop networks and 260 €/m for the tree network. These referred to the Danish context based on data from industrial partners. More general details for the Danish context can be found in Ref. [23]. The extra cost for substations' in the double loop network due to the micro tank was estimated to be 400 € per each unit. Table 2 presents a summary of the data.

Table 2. Other capital and operating costs.

		Double Loop Network	Tree Network	Individual Heat Pumps
Pipe costs	€/m	270	260	-
Micro tank	€	400	-	-
Electricity price	€/kWh		0.3	

The heat prices used for the analysis varied according to the assumed energy generation and the scenarios investigated; these are expressed in €/kWh and presented in Section 5.3. They took into account the efficiency of the energy generation as well as the use of excess heating or cooling as a free energy source. Additionally, the analysis assumed a constant electricity price of 0.3 €/kWh [56]. Even if favorable taxation for electricity generated from renewable sources could reduce the cost of electricity in the future energy market [57], the assumption of a fixed price, based on current market conditions, was assumed as a conservative choice for the analysis. In addition, while the weather, capital and operating data refer to the Danish context, these can be generalized for countries with similar climate conditions, where heating demand is dominant compared to cooling. Finally, to provide a fair comparison based on the different lifetime expectations of the technologies, the investment costs were annualized over 30 years.

4. Simulated Case Studies

The investigation assumed a new urban area in Denmark, composed of 1500 single-family houses—arranged in ten clusters of 150 dwellings each—and four large commercial buildings. The total length of the distribution network was 10 km (either for the double loop or tree network), whereas the length and size of each clusters' pipes are summarized in Figure 2. Table 3 provides an overview of the main parameters for the energy demand in the area. The spreadsheet-based simulations assessed different scenarios based on (a) system hydraulics, (b) operating conditions for the entire systems in relation to energy analyses, distribution heat losses, and temperatures, and (c) cost analysis.

Table 3. Energy demand data for the area.

		Individual House	Individual Commercial Building
Number	-	1500	4
Floor area	m^2	200	60,000
SH peak demand	W/m^2	15	15
SH yearly consumption	kWh/m^2	17	17
DHW yearly consumption	kWh/m^2	13	-
SC yearly consumption	kWh/m^2	-	30

4.1. Case 1: Double Loop Network with HPs and Waste Heat Recovery

In this scenario, the double loop was investigated with ultra-low supply and return temperatures of 45/25 °C. As described in Section 2.6 and shown in Figure 5, there was an energy center close to each commercial building in the assumed area. The contribution of all groundwater systems was able to cover 60% of the total heating demand, which made use of the excess heat from the cooling systems in the commercial buildings, as they had a yearly space cooling consumption of 30 kWh/m^2. The remaining 40% of the energy demand was met by using air source heat pumps (ASHPs). Monthly average outdoor air temperature were used to calculate the coefficient of performance (COP), according to the Danish Energy Agency guidelines, and summarized as yearly averages in Table 1 [54]. This approach was used for the ASHPs included in the analysis of Case 2–4. The authors also assessed the impact, technically and economically, of other local excess heat sources (e.g., data centers, supermarkets, industries, etc.) by varying their contribution from 0% to 100% of the total energy demand. This was performed for both Case 1 and 2.

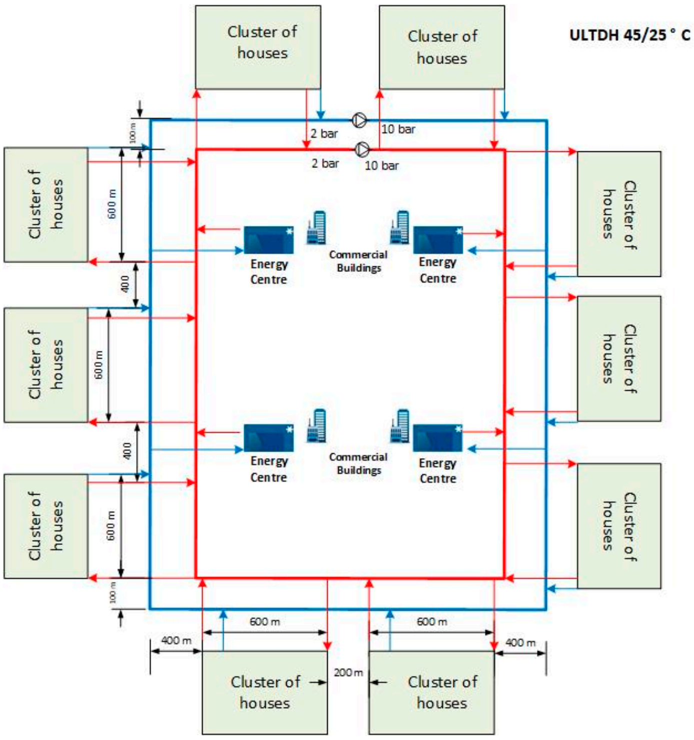

Figure 5. Double-loop configuration for the area.

4.2. Case 2: Double Loop Network with Large ASHPs

The scenario in Case 2 investigated the same double loop concept, as illustrated by Figure 5, but with heat produced by large ASHPs in the energy centers. Cooling for the commercial buildings was based on central air-conditioning systems and therefore not included in the analysis of the district network design and operation.

4.3. Case 3: Tree Network with ASHP

In this scenario, a typical tree network, as shown in Figure 6, was assumed with a central energy generation site based on large ASHPs with operating network temperatures of 55/25 °C. As the supply temperature, in this case, was 55 °C, sanitary water was safely delivered without using electricity to increase the DHW temperature. Street and substation bypass valves were considered in the analysis as no loops were assumed in this case.

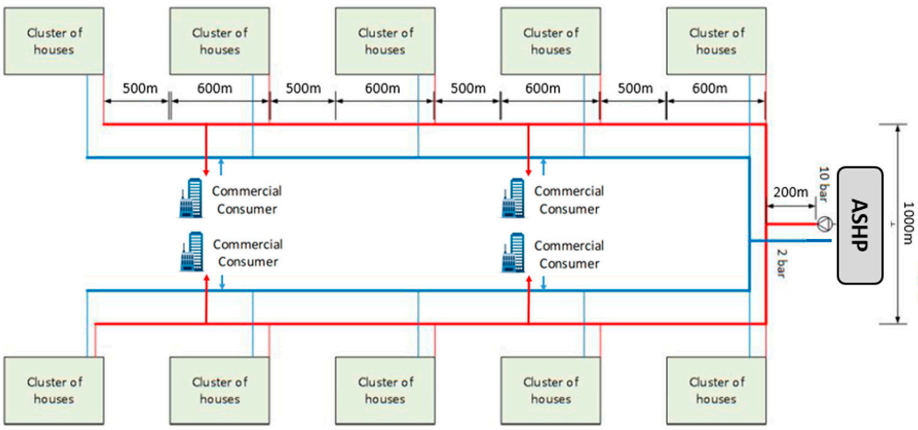

Figure 6. Tree network schematics for the assumed area.

4.4. Case 4: Individual Heating Solutions Based on Heat Pumps

In this scenario, it was assumed that individual ASHPs were installed at each end-user to meet the SH and DHW demand, as summarized in Table 1.

5. Results and Discussion

5.1. Network Design and Hydraulics

The design mass flow rate was calculated as described in Section 3.1.1, and the results for the double loop (e.g., clusters and main loops) and tree network are summarized in Table 4. In the double loop configuration, a pressure drop of 8 bar was available for both the main loops and each cluster due to the presence of local and main pumps. This yielded a double loop network with a pressure gradient of 570 Pa/m in the clusters and 80 Pa/m in main loops. The tree network was designed with a pressure gradient of 67 Pa/m from the main pump to the critical end-users in the furthest cluster. The velocity was in all cases below 3 m/s, thus avoiding the risk of noise for the end-users.

Table 4. Pressure gradient and design mass flow rate for the network.

		Double Loop—Cluster	Double Loop—Main Loop	Tree—Cluster	Tree—Distribution Network
Pressure gradient	Pa/m	570	80	98	67
Design mass flow	kg/s	5.4	96.4	3.6	64.3
Maximum velocity	m/s	1.94	1.78	0.74	1.50

Twin pipes were selected everywhere in the network and the design parameters are included in Table 5. The critical design situation for the main distribution loops was to have one of the local heat sources, randomly distributed in the area, capable of delivering 100% of the heat demand. Hence, the design established the same diameter (264 mm) everywhere in the 10 km distribution loops to increase the system's flexibility. This allowed the heat source to be placed anywhere and the maximum flow rate to be circulated in the loop without any hydraulic limitation and with lower total pressure loss. From a design perspective, this was selected because the improved operation and flexibility compensated for the slightly increased costs and heat losses. Rather, to minimize distribution heat losses in networks, it was more advantageous to reduce the service pipes as much as possible. In fact, the total length of the service pipes was 22.5 km, compared to the 10 km of the main distribution loop. The sizing of the clusters and the selection of pipes was presented schematically in Figure 2. The lowest commercial diameter of 11 mm was assumed for the service pipes, whereas diameters from 28 to 54 mm were assumed for the street and branch pipes.

Table 5. Design parameters for the pipe selection.

		Double Loop		Tree	
		Winter	Summer	Winter	Summer
Supply temperature	°C	45	45	55	55
Return temperature	°C	25	15	25	33
Pipe burial depth	m	1			
Soil temperature	°C	8			
Soil thermal conductivity	W/mK	0.16			

Figure 7 presents a comparison between the pressure profiles at the design conditions for the double loop network, with either one heat source or five decentralized heat sources, and the tree network (Case 3). As is typical in tree network pressure profiles, the main pump ensures the necessary pressure head based on the signal from the differential pressure sensors installed at the critical user in the network. This results in an uneven pressure difference among the users according to their distance from the main pump, while pressure control valves regulate the flow and ensure a hydraulically balanced network. While it is a robust and commonly used technical solution, this can limit the capability of tree layout networks to integrate unplanned decentralized heat sources due to the relative variation of pressure levels that the feed-in flow can generate [36,37].

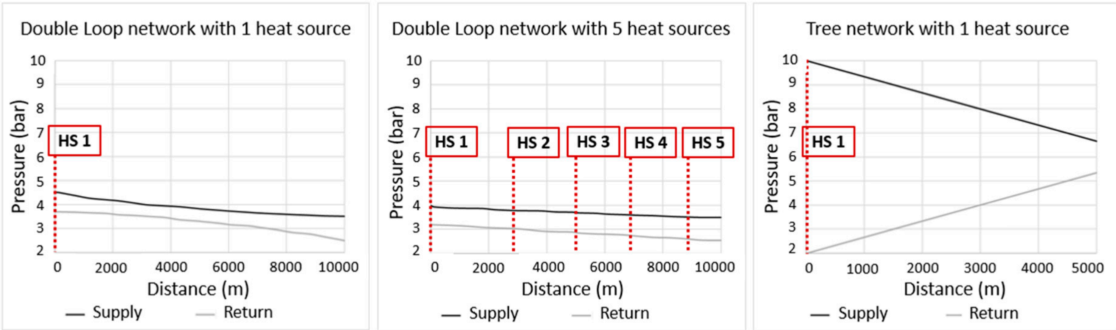

Figure 7. Comparison of pressure profiles for the double loop network (with one and five heat sources) and the tree networks. All cases' hydraulics are at the design condition.

Conversely, the pressure profiles for the double loop network showed a uniform pressure difference along with the distribution network. The local pumps have the role to control the pressure in the clusters, which replaces the function of pressure valves in typical tree networks and separates the hydraulics of the main distribution from the local operations.

5.2. Energy Analysis of Simulation Cases

The duration curve, as presented in Figure 8, illustrates the total heat demand for SH and DHW, assuming the same profiles for each type of building connected to the DHC network. The distribution heat losses were also included in the network duration curve according to the Case considered. The electricity consumption for DHW preparation in Case 1 and 2 was not included in the duration curve. The curve highlights how design conditions rarely occur and the systems are in part-load operation during most of the year. Typically, morning peaks during winter, as a combination of DHW demand and reheating of the buildings due to night set-back, have the effect to create capacity problem in existing DH networks. As a result, DH operators normally increase the supply temperature to deliver heat to the end-users. The effect is an increased return temperature and the necessity to turn on expensive fossil fuel boilers [4]. In the investigated cases, no night setbacks were assumed for the low energy buildings and as the main loops were designed with the same diameter everywhere—see Section 5.1, this would avoid capacity problems in the network and the relative side-effects.

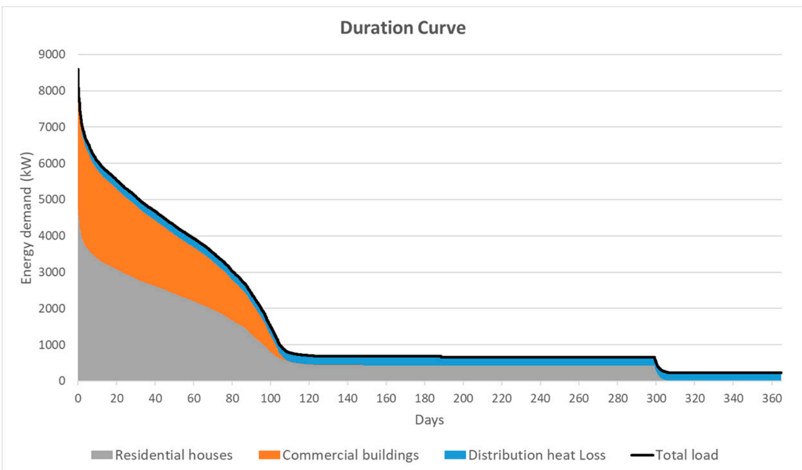

Figure 8. Network duration curve for the new urban area.

Figure 9 presents an energy comparison for all of the simulated cases. Firstly, the typical range for pumping energy in DH networks is 0.5–1% of the total energy consumption and it is not a loss for the system as they used electricity is converted into useful heat due to frictions of water flows in the pipes [4]. The pumping energy is calculated per each part-load operation based on the duration curve presents in Figure 8. The energy balance highlighted how, despite the large use of pumps for operating and controlling the double loop network, the impact of pumping energy was equal to 0.9% of the total final energy consumption, where 78% was due to the pumps in the clusters and 22% for the pumps in the main distribution loops, for both Cases 1 and 2. Additionally, the combination of ultra-low operating temperature and the exclusion of the circulation in the service pipes during summer and no-load periods led to distribution heat losses of 12% of the total energy delivered in the network. For the tree network (Case 3), the distribution heat losses were 19%, while the pumping energy was 0.6% of the total energy final energy consumption. The possibility to circulate the supply flow without the need for bypass valves to maintain the required temperature in the looped networks has another advantage: a reduction of the yearly average return temperature from 33 °C in the tree network to 23 °C in the double loop for Cases 1 and 2. In addition, it should be noted that there was an increased electricity consumption in Cases 1 and 2 due to the electric resistance heating in the micro-tanks, whereas all heat demand was covered by individual heat pumps in Case 4.

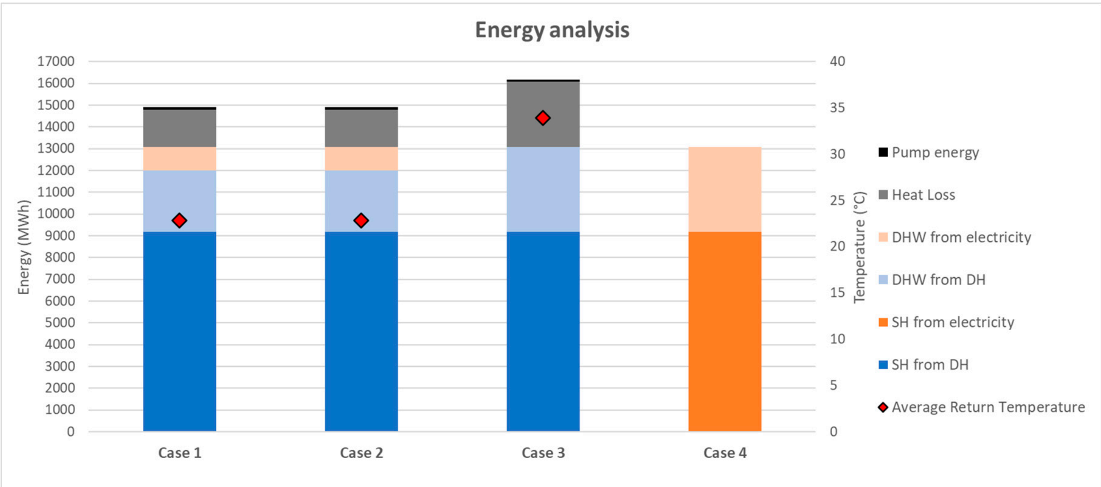

Figure 9. Comparison of energy analysis of simulated scenarios.

5.3. Cost Analysis of Simulation Cases

Figure 10 presents a cost comparison of the simulated cases. Although the double loop networks in Cases 1 and 2 were designed for ultra-low temperatures and smaller ΔT, the increased capital costs for pipes were only 8.5%. The reduced pipe diameters were the result of the booster pumps in the systems and the high pressure-gradients in the clusters that helped minimize the pipe diameters at the design stage as described in Section 5.1.

The micro tanks were 5% of the total capital expenditures (capex) for Cases 1 and 2. However, the micro tanks provided the advantage of reducing the distribution of heat losses from 19% to 12% by avoiding circulation in the service pipes during summer. This helped to achieve a yearly average energy weighted return temperature of 23 °C. Furthermore, operating the system with ultra-low temperatures improved COPs and integration of low-temperature heat sources. Conversely, the temperature requirements for DHW preparation influence the electricity consumption of the micro tank. Higher DHW temperature set-points yield higher electrical consumption and costs, as the electricity price of 0.3 €/kWh is larger than the heat price as summarized in Table 6. For instance, Case 2, which used ASHPs for all heating, resulted in larger costs compared to the tree network in Case 3 due to the greater cost of electricity necessary for DHW preparation.

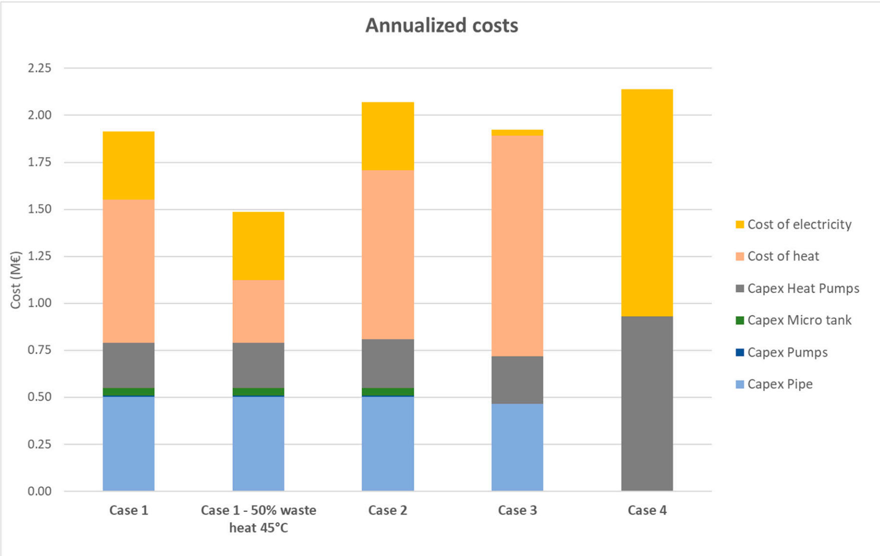

Figure 10. Annualized cost comparison of simulated cases (Case 1 assumed 50% recovery of waste heat).

Table 6. Heat price for different cases.

		Case 1	Case 2	Case 3	Case 4
Heat price	€/kWh	0.056	0.066	0.073	-
Heat price with waste heat at 30 °C	€/kWh	0.025	0.025	-	-

Instead, Case 1 was competitive with all the other cases, even in the reference scenario with 60% heat from the groundwater systems and 40% from ASHPs—see Sections 2.6 and 4.1. When it was assumed that 50% of the total heat demand was from waste heat recovery in Case 1, it gave the best economic performance as depicted in Figure 10. Integrating free energy sources has a significant impact in reducing the overall costs in district heating operations, and it will be crucial for the future competitiveness of DHC technology. Section 5.5 provides a more detailed investigation about the impact of the waste heat recovery from 0% to 100% to the costs of the double loop networks at different temperatures' level. Finally, Figure 10 also indicated that the scenario with individual heat pumps presented for Case 4, even for a low heat density area, had the highest capital and operating costs. Hence, in line with the findings of Refs. [23,58], the district heating networks were technically and economically more feasible than the individual heat pump solutions due to the economies of scale and higher efficiency of the energy generation.

5.4. Summer Circulation Flow

During summer, the flow to be circulated has to compensate for the temperature degradation due to the distribution heat losses and must ensure 45 °C in the street pipe at the longest distance from the main pump. In general, higher circulated flows result in lower decreases in temperatures is in the supply line. The optimal flows were calculated for the main loops and clusters in Cases 1 and 2 by minimizing the sum of costs related to the distribution of heat losses and the pumping energy. These corresponded to the minimum points in the curves presented in Figures 11 and 12.

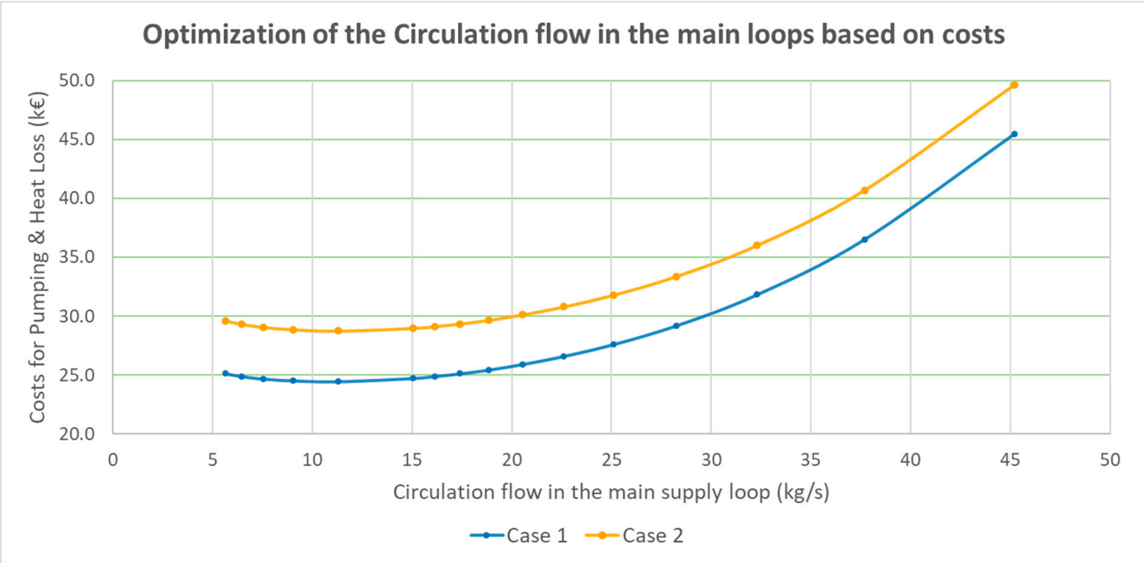

Figure 11. Optimal summer circulation flow in the main supply loop.

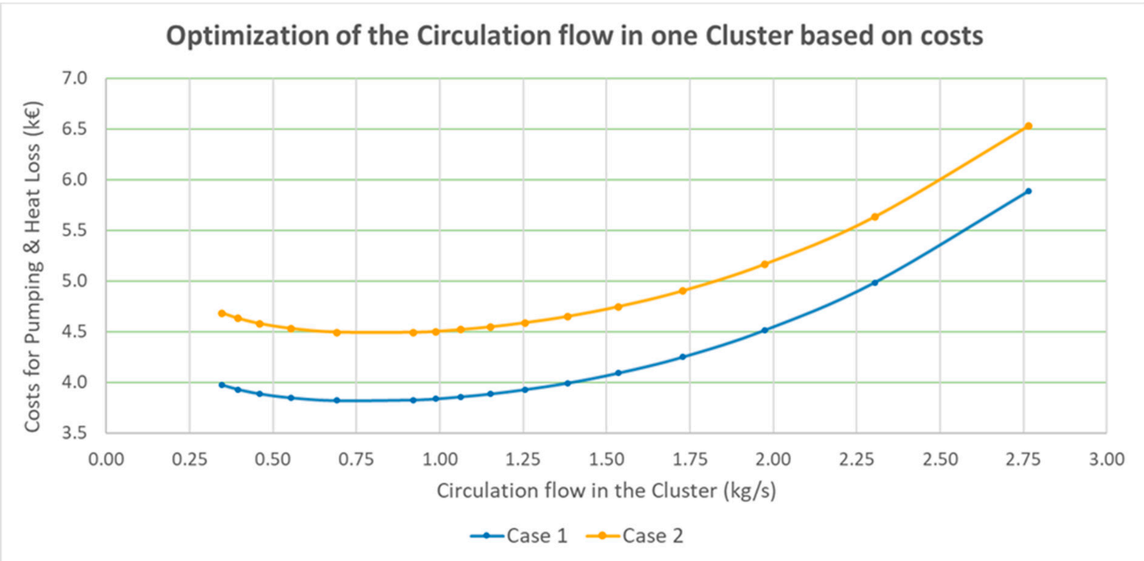

Figure 12. Optimal summer circulation flow in the cluster.

Hence, for Case 1, the optimal supply temperature was 53.2 °C for a ΔT of 4 °C and a mass flow rate of 11.3 kg/s in the main loop; whereas, in the clusters, the optimal flow was 0.75 kg/s for a ΔT of 3.3 °C. For Case 2, the optimal flow was 11.40 kg/s for a ΔT of 3.9 °C in the main loop with a supply temperature of 52.9 °C; whereas it was 0.82 kg/s for a ΔT of 3.2 °C in the clusters. This clearly highlighted that increasing the circulations flow to achieve lower ΔT did not always result in lower operating costs for the networks.

5.5. Impact of Recovering Excess Heat

One of the key improvements of the double loop concept is the high flexibility to integrate excess heat from local producers randomly located in the network. This was investigated for both Case 1 and 2 and the results in Figure 13 illustrate the variation of the waste heat recovered from 0% to 100% as a proportion of the total heating demand as well as its relative impact on annualized costs. Both Case 1 and 2 were evaluated with waste heat temperatures of either 30 or 45 °C. In the scenario with excess heat temperatures of 45 °C, a direct connection to the supply line of the main loop with an R/S connection was feasible. For the scenario with 30 °C, it was assumed that the heat was fed in the return line of the network with an R/R connection—which increased the return temperature—and that a central heat pump cooled down the return temperature to 25 °C while delivering heat to the supply line at the optimal temperature of 45 °C. As a conservative choice, the capital investment for heat production capacity was maintained for all scenarios regardless of the local availability of waste heat to always ensure a backup solution in the system.

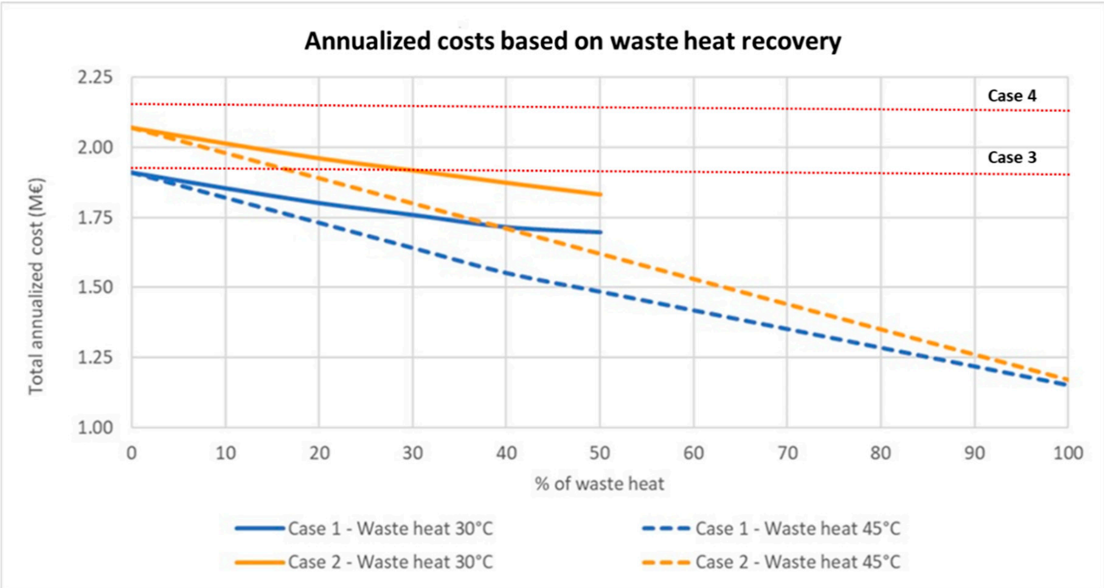

Figure 13. Total annualized cost as a function of the share of total heat demand recovered from waste heat sources.

Overall, more waste heat recovery leads to lower annualized costs. Case 1 was cost-competitive with all cases even for the scenario with no waste heat recovery due to the lower cost of heat, see Table 6; whereas Case 2 became more cost-competitive than the tree network (Case 3) as presented in Figure 13 when waste heat recovery was more than 17% of the total demand with waste heat temperatures at 45 °C and 30% with waste heat temperature at 30 °C. However, based on the network design, a maximum of 50% of the heat demand could be recovered from waste heat sources at a temperature of 30 °C due to the hydraulic limitation in the return line. For integrating a larger proportion of excess heat at 30 °C with R/R connections, larger diameters would be necessary for the main loops. Finally, as the cost of heat from ASHPs was higher than the heat produced by the groundwater systems, for Case 1 with waste heat at 45 °C, the curve in Figure 13 is steeper in the interval 0–40% as the contribution of ASHPs was replaced by free waste heat; for the scenarios with waste heat at 30 °C, the slopes of both curves were changing due to the increased pumping costs associated with the R/R connection.

5.6. Micro Tanks on the Primary Side for DHW Preparation

The micro tanks installed in each substation required a volume of 10 L and an electric heater of 1.9 kW to heat the water volume from 45 °C to 100 °C in 20 min. The volume also takes into account the 12 s time delay necessary to flush the water volume stored in the 11 mm service pipe at a ground temperature between draw-off intervals. Electric power of 1.9 kW is generally compatible with a typical domestic connection to the electric grid, so it did not require any extra costs or arrangements. The volume was calculated based on the draw-off program defined in the Danish standards DS 439 and described in Section 2.5. In case of larger peaks and/or different profiles with a shorter interval between draw-offs, the volume of the tank should be designed based on this new scenario. The heat losses were minimized due to the vacuum insulation and were assumed to be 11 W according to Ref. [59]. Although the micro tank increased the substation costs, the substation represented only

5% of the total capital costs, as presented in Figure 10. The electricity used for heating the water volume in the tank, as a function of the set-point temperature in the primary side of the heat exchanger, had an impact on the total costs ranging from 16–28% for Cases 1 and 2, depending on the proportion of the excess heat recovered as described in Section 5.5. The electric heaters in the micro tanks had the effect of increasing the use of electricity for DHW preparation, as this was a function of the set point temperature in the primary side, which had an impact on the operating costs and economy of the double loop network. The investigation was based on the conservative choice of having 55 °C and 50 °C on the primary and secondary sides, respectively. However, the European recommendations for the prevention of Legionella growth in DHW installations [60] suggest 50 °C in all points of hot water systems with circulation and 60 °C in hot water storage. Instead, for systems with instantaneous DHW preparation and no circulation and water storage, there are no restrictions except for comfort temperature minimums of 45 °C for kitchen use and 40 °C for showers if the water volume in the DHW pipes is less than 3 L. Hence, the authors recognize that new studies documenting the risk of Legionella for those cases as a priority in the field. The possibility to lower set-point temperatures for DHW systems could be essential for further reducing the operating temperatures in the networks in particular for urban areas with low energy buildings. This will be crucial for the competitiveness of DHC in the future energy market where electricity and heating will be highly integrated to better exploit renewable energy generation.

5.7. Cooling Operation of the Double Loop

Residential cooling is not common practice in Denmark based on the climate conditions, but the improved network design and operation with the double loop network led to an assessment of cooling potential during summer using the return pipelines. The assessment was based on Case 1, and it was assumed that the groundwater at 10 °C, located in the energy centers near the commercial buildings, was used as a free cooling source. The end-users substation arrangements, including the cooling substation, were described in Section 2.5 and illustrated in Figure 3. The schematics of the cooling operations in one of the return street pipes in one cluster is presented in Figure 14. The temperature increased along the return street pipe from 10 °C at the entrance to 22 °C after the last connected end-users due to mixing with the return water after delivering cooling. As highlighted in Figure 14, due to the increased temperature in the direction of flow, the local pumps have to increase the local flow to ensure the same cooling power to all end-users.

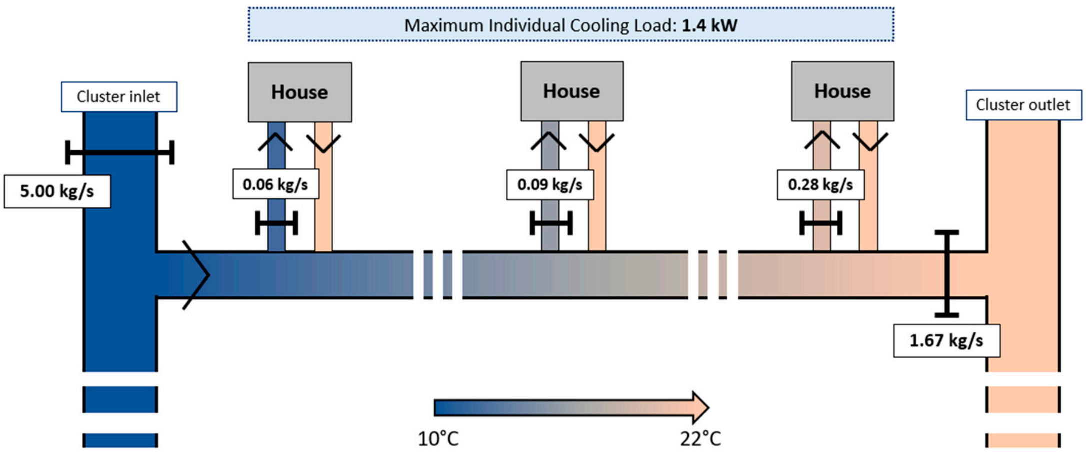

Figure 14. Cooling arrangement in the clusters.

The calculated maximum deliverable cooling load was 1.4 kW per house, corresponding to 47% of the winter design heat load of 3 kW. The maximum cooling capacity was limited because the network was designed based on peak heat demand with a ΔT of 20 °C, whereas DC networks are typically designed and operated with smaller Δ*T* in the range of 10–15 °C. However, the achievable cooling capacity was satisfactory for a newly-built house under typical Danish climate conditions to maintain an indoor temperature of 25 °C and ensure the required comfort.

Delivering cooling would require extra cost for each end-user substation, due to the need for having an extra service pipe as well as a local circulating pump and an R/R connection to the street return pipe. Hence, the authors estimated 27% more costs for a combined heating and cooling network, which is economically attractive in comparison to having a separate district cooling network.

The cooling operations, based on a smaller Δ*T* [4], have a larger impact on the pumping energy and costs compared to the heating operations. Hence, the influence of increasing the diameter of the service pipes was investigated in pumping energy consumption. As depicted in Figure 15, it was found that by selecting a commercial diameter of 16 mm instead of 11 mm, the energy consumption of the domestic cooling pumps was reduced by 78% due to the lower pressure losses in the service pipes.

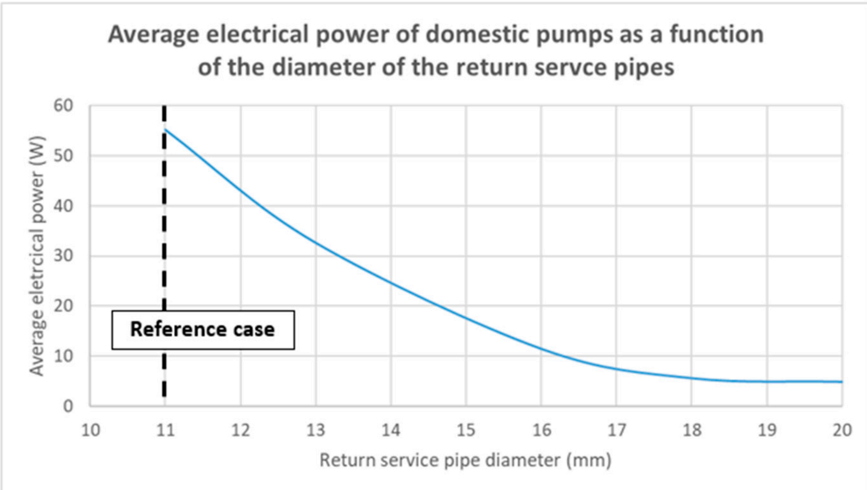

Figure 15. Improved pump operation as a function of service pipes' diameters.

Similarly, the investigation assessed the possibility to increase the deliverable maximum cooling load by choosing larger pipe diameters in the clusters. The results showed that using an average pipe diameter of 70 mm instead of 37 mm—as in the reference design case in Figure 2—doubled the cooling load to 3 kW as shown in Figure 16.

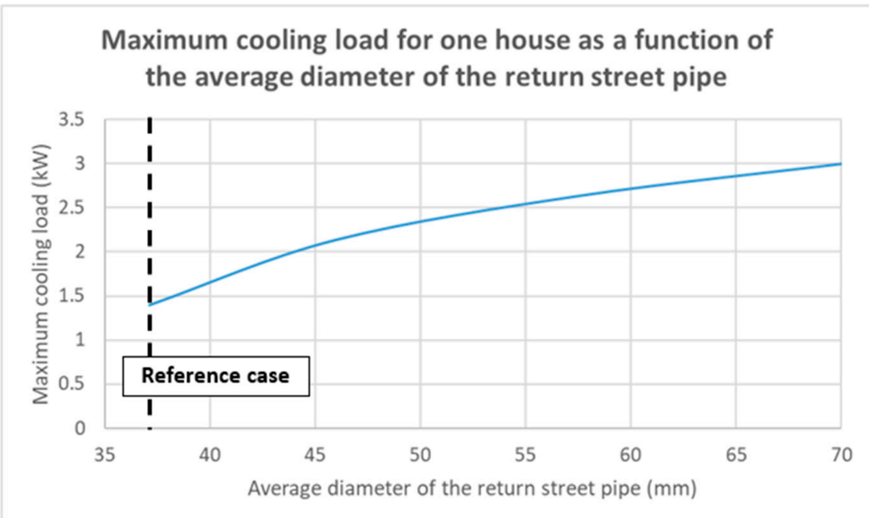

Figure 16. Cooling load per house as a function of the street pipes' diameters in the cluster.

This Section assessed the potential of the concept to embed heating and cooling in the same infrastructure. The optimal operations and costs analysis of cooling in the double loop network was not included in this analysis and will be investigated in a separate study.

6. Conclusions

The energy analysis of the proposed double-loop network highlighted how despite the important role of pumps in the operation and control of the system, the pumping energy consumption was 0.9% of the total energy consumption and is still an order of magnitude lower than the distribution heat losses. Hence, it is a good design strategy to make use of a larger pressure gradient to size the networks if possible as this leads to reduced pipe diameters, lower investments, and lower distribution heat losses. In fact, the combination of optimized design and lower operating temperatures led to distribution heat losses of 12% of the total final energy consumption for the investigated double-loop networks compared to 19% for the tree network. This is quite important as distribution heat losses are crucial for the DH competitiveness in particular for areas characterized by low heat density.

Another key element for the future competitiveness of DHC technology will be the capability of networks to integrate decentralized heat sources and recover excess heating or cooling. The investigation showed that an increased share of waste heat recovery reduced the overall costs compared to all other investigated scenarios, including that with individual heat pumps. It was possible to integrate a large share of unforeseen waste heat in the double loop cases due to the improved flexibility of the system—as a result of the uniform pressure distribution in the network—and the potential to circulate both supply and return water flows separately. This represented an enhancement compared to typical tree network layouts.

Despite the increased capital costs of 5%, the integration of a micro tank in the substation of each end-user had two main advantages: the possibility to use ultra-low temperatures and the avoidance of *'keeping the service pipes warm'* during summer operations or no-load periods. These advantages, in combination with the possibility to circulate the supply flow without the need for bypass valves, helped minimize the distribution heat losses and achieved a yearly average return temperature of 23 °C. Further studies documenting no risk of Legionella bacteria with lower set-point temperatures for instantaneous DHW preparation systems can improve the overall economy of the proposed concept due to the lower electricity consumption of the micro-tank electric heaters.

The use of individual heat pumps as an alternative solution for low heat density areas indicated that district heating networks could be competitive due to the higher achievable efficiency of larger heat pumps, the capability of recovering waste heat, and the increased cost efficiency due to the economies of scale.

Finally, although few in Denmark envisage residential cooling as a priority, this study investigated the potential of embedding heating and cooling in the same infrastructure. This was possible due to the separate circulation of supply and return flows in the double loop network layout without the need for bypass valves. Hence, the proposed concept was able to supply 1.4 kW of cooling to each end-user, which corresponded to 47% of the total design heat load of the double loop network. Due to the promising results, the double loop concept will be further investigated with a focus on climates where cooling demand is dominant compared to heating demand. This will lead to a different approach and optimization of the system, depending on the availability of local cooling sources and the overall network design, which will be based on peak cooling demand and lower ΔT.

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Nomenclature

List of Symbols and Acronyms

DH	District heating
DC	District Cooling
LTDH	Low-temperature district heating
4GDH	4th generation district heating
5GDHC	5th generation district heating and cooling
EED	Energy Efficiency Directive
EPBD	Energy Performance of Buildings Directive
ΔT	Temperature difference between supply and return (°C)
SH	Space heating
DHW	Domestic hot water
R/S	Return/supply connection of decentralized energy source
R/R	Return/return connection of decentralized energy source
COP	Coefficient of performance
HP	Heat pump
cp	Specific heat capacity of water (kJ/kg °C)
Ts	Supply temperature (°C)
Tr	Return temperature (°C)
$\dot{m}$	Mass flow rate (kg/s)
ASHP	Air source heat pump
WSHP	Water source heat pump
HS	Heat Source
LMTD	Logarithmic mean temperature difference
DPC	Differential pressure controller
CHV	Check valve
TMV	Thermostatic valve

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