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Cascade sub-low temperature district heating networks in existing district heating systems

Anna Volkova [a, *], Stefan Reuter [b], Stefan Puschnigg [c], Hanne Kauko [d], Ralf-Roman Schmidt [b], Benedikt Leitner [b], Simon Moser [c]

[a] Tallinn University of Technology, Ehitajate Tee 5, 19086, Tallinn, Estonia
[b] AIT Austrian Institute of Technology GmbH, Giefinggasse 4, 1210, Vienna, Austria
[c] Energieinstitut an der Johannes Kepler Universität Linz, Altenbergerstrasse 69, 4040, Linz, Austria
[d] SINTEF Energy Research, Sem Sælands Vei 11, 7034, Trondheim, Norway

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ABSTRACT

Existing district heating networks (DHNs) are often designed for relatively high temperatures, typically 80–120 °C supply and 40–60 °C return. The transformation of such high-temperature DHNs (HTDHNs) into more efficient low-temperature DHNs (LTDHN) and towards the 4th generation DHNs is associated with great complexity and effort. This paper discusses the integration of sub-LTDHNs into the return flow of existing HTDHNs, thereby creating an energy cascade and thus lowering the overall system temperatures of the HTDHN. The technical barriers and drivers of such sub-LTDHNs were analysed through literature research, expert interviews, and a questionnaire. Their technical design was investigated, and a techno-economic analysis was conducted for several configurations in terms of the supply and return temperatures in the sub-LTDHN, various temperatures of the HTDHN and potential connecting points. This analysis was also conducted for a planned residential area in a Nordic city. In addition, their operating dynamics resulting from different HTDHN load conditions were analysed in terms of the effects on the sub-LTDHN. It was found that, on the one hand, the connection point with its prevailing conditions (mass flow and temperature) is the key parameter to ensure that the heat demand is met. On the other hand, the savings in the HTDHN due to lower return system temperatures resulting from the sub-LTDHN integration in the return pipeline are significantly higher if the use of combustion technologies is minimized.

1. Introduction

Today's district heating networks (DHNs) are characterized by high supply temperatures and heat supply from centralized heat generation plants. 4th Generation District Heating (4GDH) and smart thermal grids to supply buildings' heating demands are key enablers in the transition to sustainable energy systems [1–3]. Reduced temperature in DH systems, low heat transmission loss, the use of renewable and excess heat, and the capacity to be integrated into smart energy systems are all characteristics of the 4GDH idea [4]. Due to reduced heat loss and the potential to utilise renewable energy sources, heat supply via sustainable low-temperature DHNs (LTDHNs) is recognised as one of the most advantageous options for urban structures [5]. Moreover, lower supply temperatures increase the efficiency and reduce the cost of integrating large-scale heat pumps into DHNs, which is an important step in facilitating the integration of variable renewable energy sources into the power grid [6] and making DHNs an active component of future smart energy systems [7]. Hence, a number of stakeholders will benefit from lower temperatures, including the energy supply and transition system, as well as end users.

The transition to lower temperatures can be difficult or even impossible in some cases to when there is already a well-established high-temperature DHN (HTDHN), mostly providing heat generated by Combined heat and power (CHP) plants and boilers, along with an established stock of buildings and their installations [8]. There are various reasons for this, e.g. recent investments in energy efficiency of existing DHNs, consumers who are not ready to switch to low-temperature heat supply, the lack of low-temperature heat sources nearby, etc. As a rule, areas that

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* Corresponding author.
E-mail address: anna.volkova@taltech.ee (A. Volkova).

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could be supplied with low temperatures are nevertheless connected directly to the HTDHN because it is the simplest solution [9]. In this case, it is not possible to take advantage of the opportunities offered by energy-efficient buildings to improve heat supply. One possible solution for transition to LTDHNs in such building areas is to connect them to the return pipeline of existing DHNs. As a result, sub-LTDHN the return temperatures of the HTDHN can be reduced and thus the overall efficiency improved.

In this paper, such local LTDHNs which are connected to the HTDHN via the return pipeline shall be called a low-temperature sub-LTDHN (sub-LTDHN). This kind of solution will be implemented in parallel with the normal operation of the HTDHN. Additional heat may from the supply pipeline may be required to raise supply temperature in the sub-LTDHN during periods when the temperature level in the return pipeline is not high enough. In a previous study [10], a generic definition of sub-LTDHN was proposed, which suggests that the sub-LTDHN is connected to an existing HTDHN that exhibits relatively high network temperatures. A sub-LTDHN connects several low-temperature consumers via a sub-LTDHN, i.e. the consumers are not directly connected to the HTDHN's return pipeline.

According to the definition, the purpose of the sub-LTDHN is to utilise low-potential energy in the network based on consumer needs to make the best use of the available energy resources and network capacities. Alternative low-grade heat sources that are available nearby can be directly used by sub-LTDHNs.

1.1. 1. state of the art

There are several studies on the topic of implementing this type of solution, as well as its benefits, barriers and drivers.

One of the first descriptions of energy cascade solutions was presented in Ref. [11]. The paper described the results of a two-year monitoring with detailed measurements of an area of low heat density in Denmark with 40 low-energy terraced houses that partly use return water from existing networks to supply district heating. Reducing the return temperature was analysed in a different study [12] as one of the key benefits. A subsequent study presented an analysis of an efficient method for maintaining low-energy buildings using a return pipeline from a high-temperature DH [13]. The results show that connecting the area to the return pipeline of the HTDHN can cover 20—50% of the annual heat demand of low-energy buildings.

The possibility of developing concepts for reducing the DH return temperature was assessed in Ref. [14]. In this study, several inputs were considered for modelling an energy cascade in various scenarios, including supply temperature, return temperature, volume flow rate, and heat demand. The study showed that the maximum return temperature reduction can be achieved during the heating season. The technical and economic feasibility of integrating the energy cascade LTDHN into the existing large-scale HTDHN was investigated in Ref. [9]. Various solutions were evaluated from an economic standpoint. The most technically feasible solution was then compared to the reference solution. The results showed that a decrease in the return temperature leads to an increase in electricity generation at the CHP plants, an increase in heat recovery, and a decrease in heat loss. Nevertheless, this option comes with additional costs. The development of cost-effective and environmentally friendly solutions for LTDHNs using four representative case studies from Austria was described in Ref. [15]. Scenario analysis was conducted with both economic and environmental concerns in mind. The results suggest that LTDHNs can be a cost-effective, environmentally friendly and energy-efficient solution for space heating and domestic hot water production, but the optimal design and operation strategies are highly dependent on local conditions and cannot be solved in a generalised manner. Another study has focused on developing business models that can dramatically reduce temperatures in existing DH systems and enable transition to 4GDH [16]. Particular emphasis was given to solutions that encourage deeper implementation of demand-side measures to reduce the return temperature in the network. Motivational pricing was proposed to achieve this goal by offering a discount on heat taken from the return pipeline. This approach is expected to encourage consumers to install low-temperature systems. The connection of the LTDHN to the return pipeline of the existing HTDHN system in Nottingham that created the first LTDHN of such scale in the UK was analysed in Ref. [17]. This analysis includes an assessment of whether this option would make the heat supply more efficient and profitable.

1.2. Aim of the paper

The overall goal of this study is to develop and expand on the existing analyses of the potential for sub-LTDHN implementation. The specific aim is to conduct a more detailed study on the suitability and usefulness of sub-LTDHNs to stimulate their future integration. Technical barriers and drivers were specifically elaborated on and assessed. The techno-economic analysis evaluated the overall system behaviour, including the HTDHN. In particular, the influence of the varying return temperature of the HTDHN and the integration point of the sub-LTDHN were investigated. In addition, dynamic modelling of the temperature and mass flow parameters was performed to test system suitability and identify potential issues and bottlenecks. The economic analysis considered the effects and savings from the HTDHN point of view due to the integration of sub-LTDHNs into the return pipeline and the subsequent reduction of system temperatures.

The paper is structured as follows: the 2nd Section provides the research methodology for the identification of the main barriers and drivers and techno-economic analysis of the sub-LTDHN. The 3rd Section presents the list of identified barriers and drivers, the results of the techno-economic analysis, including the case study of a Nordic city, as well as the results of the study on operational dynamics. The conclusions are presented in the 4th Section.

2. Methods

This section describes the process for ranking barriers and drivers, and a two-part techno-economic analysis method. The first part includes a high-level technical assessment of cascading sub-LTDHNs and an economic analysis based on the benefits of the reduced return temperature. The second part examines the operational dynamics of an HTDHN to which a sub-LTDHN is connected via cascading, focusing on off-design cases.

2.1. Determination and ranking of barriers and drivers

Implementation of cascading solutions involves several barriers and drivers. The introduced generic definition in Ref. [10] shows that there are certain conditions that must be met to implement this solution. This means that if one or more conditions are not met, it will become a barrier to successful implementation. Based on this definition, the following technical barriers will prevent this option from being implemented:

- No HDHNs in the vicinity of the potential sub-LTDHN;
- Insufficient heat load for potential area;
- Buildings/districts cannot be connected to LTDHN, due to design of building installations for space heating and domestic hot water

Another set of barriers may reduce the feasibility of the implemented solution, but, nevertheless, this option remains possible. The following barriers are included in this group:

- Insufficiently high temperature of the return pipeline;
- Additional costs associated with connections of sub-LTDHN.

To identify the barriers and drivers associated with the implementation of the energy cascade solution, the main benefits and beneficiaries of this solution should be discussed first. Based on the case described in Ref. [9] and studied in Ref. [14], the following benefits of this solution were identified:

- Benefits associated with lower return temperatures: reduced heat loss in the HTDHN, increase in electricity generation at CHPs, and increased heat recovery in flue gas condensers (boiler houses and CHPs); higher efficiency of excess heat utilisation, geothermal and solar thermal energy as well as heat pumps.
- Benefits associated with the integration of LTDHN: reduced heat loss in the subLTDHN, increased potential for the direct integration of local renewable energy sources, and reduction in pumping costs due to the decrease in the network's mass flow per MWh delivered;
- Possibility of increasing the network capacity without installing additional heat generation units and transmission lines.

The benefits and beneficiaries of this type of solution depend on the business models and tariff systems implemented in the country. In the case of a one-component tariff, the main beneficiaries are heat producers and district heating operators. In this case, reducing the return temperature will not affect the cost of heating for consumers, so this most likely will not lead to increased interest in the solution from stakeholders (including developers). Because the benefits obtained by the operator can only be observed in the long term, district heating consumers will only benefit indirectly under these economic circumstances. Stakeholders such as real estate developers and district heating end users can benefit from this kind of solution only in the case of a more complex tariff system.

It is important to note that all the benefits associated with the implementation of a LTDHN (see above) apply also to the cascade solution, as it will allow implementing a LTDHN quickly, at low cost, and in parallel with the existing large DHN. In addition, it can help prepare the existing DHN for the future transition to 4GDH.

In the previous study in Ref. [10], the following groups of non-technical and technical barriers were identified. Legal, economic and organizational barriers are important and can be found in this study. This paper focuses on technical barriers.

The barriers, shown in Table 1 were collected through the following channels in the frame of this research:

- literature review based on [9–18];
- analysis of implemented cases;
- meeting with experts (workshop with 30 experts);
- questionnaire (both for ranking and for identifying barriers with an option to add your own answers).

The questionnaire was sent to experts and representatives of district heating companies, and 112 respondents from several countries completed the survey. Of the total number of respondents, 45% were district heating companies, 34% were researchers, and 21% were expert consultants and engineers. The main goal of survey was ranking of barriers, thereby identifying the most significant ones. Likert scale has been used for evaluation, where each barrier/driver should be evaluated from 1 to 5, where 1 means, that barrier/driver is not important at all, 2 is slightly important, 3 is moderately important, 4 is very important and 5 is extremely important. The respondents had the opportunity to provide their own answers to all questions, including questions related to technical barriers. Results on technical barriers' ranking are presented in the paper.

2.2. Techno-economic analysis (static)

The techno-economic analysis for cascading sub-LTDHNs is based on quasi-static assumptions and given network parameters. It uses simplified network behaviour in order to explore the potential of cascading from a high-level perspective.

The developed algorithm calculates various technical key performance indicators (KPI), such as the overall return temperature decrease in the HTDHN, the return temperature decrease in the local network branch of the HTDHN, to which the sub-LTDHN is connected, and the share of heat supplied from the supply pipeline of the HTDHN. Based on these KPIs, the economic analysis builds upon the findings of previous studies on the economic benefits of reducing network return temperatures for various heat supply technologies [18]. The analysis was applied to data on a new residential area to be built in a Nordic city.

The first part includes an overall technical evaluation of cascading sub-LTDHN through parameter variations of the return temperature of the HTDHN and the available mass flow in the return pipe.

Calculations for the techno-economic analysis were carried out using the Python programming language [19] and were based on the following constraints:

- Quasi-static simulation: calculations were performed only for consecutive steady states (i.e. no mass flow reversals at the connection points);
- Heat loss and transfer efficiency of heat exchangers were neglected;
- Different pressure levels were not considered;
- Radial networks: all network return temperature effects were aggregated and only one central heat supplier was assumed (various supply technologies possible).

The constraints are set to simplify the simulation since this static analysis focuses on high-level assessment of the impact of the cascading sub-LTDHN. Dynamic behaviour was explored in more detail in the second part of the analysis. Limiting the scope to strictly radial networks with a single central heat supplier is a simplification that ignores the realities of large networks. Since pumping power and the corresponding heat input to the system are not taken into consideration, heat transmission loss and heat exchanger loss can have a significant impact on temperatures and mass flows in the system. Therefore, the results of static analysis reflect general trends, supplemented by more detailed dynamic simulations.

Sub-LTDHN is connected to a branch of the HTDHN, determined by the available mass flow of the return pipe ($\dot{m}_{ret,P,local}$). An additional connection to the supply pipe was provided as a backup, as shown in Fig. 1. The parameters are described in Table 2.

Based on the given parameters of the HTDHN and the sub-LTDHN (supply temperature, return temperature and mass flow), the software calculates the required mass flow from the return pipe and supply pipe of the HTDHN to ensure that the heat demand of the sub-LTDHN is covered. The following scenarios were analysed by solving the mixing equations for given constraints (i.e. perfect heat exchangers):

Table 1
Identified barriers.

Technical barriers	Non-Technical Barriers	Drivers
• Lack of suitable network locations to install a low-temperature subnetwork	• There are no areas where low-temperature district heating can be used	• Better utilisation of generation capacity
• Low return temperature in the main district heating network	• Lack of required technical competences	• Network congestion
• Limited mass flow	• Necessity of altering existing business models	• Start locally to lower the temperature of the entire network in the longer run
• Necessity of locally boosting supply temperature	• Contractual limitations on supply temperature conditions	• Tariffs that take into account supply and return temperatures
• Hydraulic issues	• Customer relationships	• Demo projects
• More complex regulation	• High investment costs	• A suitable neighbourhood/heat customer (suited for low-temperature distribution) established in the vicinity of main heat production central
• Multiple heat sources	• Tariffs do not take into account temperatures	• Information and communication

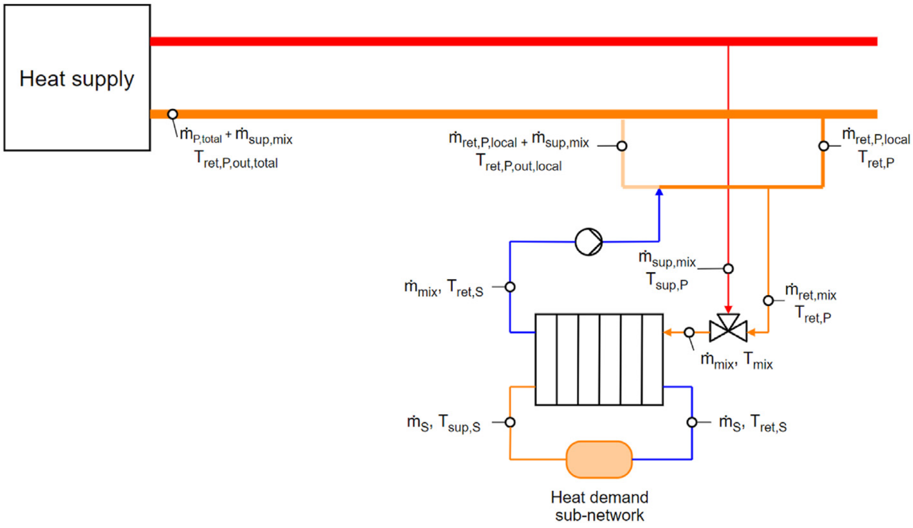


Fig. 1. General schematic of the cascading connection of a sub-LTDHN.

Table 2
Description of parameters for the cascading connection.

$T_{ret,P}$	HTDHN return temperature in local branch before cascading
$T_{ret,P,out,local}$	HTDHN return temperature in local branch after cascading
$T_{ret,P,out,total}$	HTDHN return temperature at heat supply
$T_{,P}$	HTDHN supply temperature
$T_{ret,S}$	Sub-LTDHN return temperature
$T_{,S}$	Sub-LTDHN supply temperature
T_{mix}	Temperature at inlet of cascading heat exchanger
$\dot{m}_{ret,P,local}$	HTDHN mass flow in local branch
$\dot{m}_{P,total}$	Total HTDHN mass flow
$\dot{m}_{S}$	Sub-LTDHN mass flow
$\dot{m}_{ret,mix}$	Mixing mass flow from return pipe
$\dot{m}_{,mix}$	Mixing mass flow from supply pipe
$\dot{m}_{mix}$	Mixing mass flow at inlet of cascading heat exchanger

The heat demand and supply temperature of the sub-LTDHN can only be supplied by the local return pipeline of the HTDHN: no mixing from supply pipeline is required, as shown in Equations (1)–(3), where $\dot{Q}$ is the heat demand of the sub-LTDHN, c_p is the specific heat capacity of water, ΔT_S is the temperature difference between supply and return flows in the sub-LTDHN, and ΔT_P is the temperature difference between the input and output flows on the primary side of the cascading heat exchanger.

$$T_{mix} = T_{ret,P}. \tag{1}$$

$$\frac{\dot{Q}}{c_p} = \dot{m}_S * \Delta T_S = \dot{m}_{mix} * \Delta T_P \rightarrow \dot{m}_{ret,mix} = \frac{\dot{m}_S * (T_{,S} - T_{ret,S})}{T_{ret,P} - T_{ret,S}} \tag{2}$$

$$\dot{m}_{,mix} = 0 \tag{3}$$

1. The heat demand or the supply temperature of the sub-LTDHN cannot be supplied by the local return pipeline of the HTDHN: mixing from the supply pipeline is required.
   a. The required mass flow from the local return pipeline to achieve the necessary supply temperature of the sub-LTDHN is available as shown in Equations (4)–(6).

$$T_{mix} = T_{,S} \tag{4}$$

$$\dot{m}_{ret,mix} = \frac{\dot{m}_S * (T_{,P} - T_{,S})}{T_{,P} - T_{ret,P}} \tag{5}$$

$$\dot{m}_{,mix} = \frac{\dot{m}_S * (T_{,S} - T_{ret,P})}{T_{,P} - T_{ret,P}} \tag{6}$$

b. The required mass flow from the local return pipeline to achieve the necessary supply temperature of the sub-LTDHN is not available: the maximum available return mass flow is used as shown in Equations (7)-9)

$$\dot{m}_{ret,mix} = \dot{m}_{ret,P,local} \tag{7}$$

$$\dot{m}_{,mix} = \frac{\dot{m}_{ret,mix} * (T_{ret,P} - T_{ret,S}) + \dot{m}_S * (T_{ret,S} - T_{,S})}{T_{ret,S} - T_{,P}} \tag{8}$$

$$T_{mix} = \frac{\dot{m}_{ret,mix} * T_{ret,P} + \dot{m}_{,mix} * T_{,P}}{\dot{m}_{ret,mix} + \dot{m}_{,mix}} \tag{9}$$

2.2.1. *Technical assessments*

Two cases were evaluated using the abovementioned programme. Each case was compared with the reference scenario where the sub-LTDHN is directly connected to the supply pipeline of the HTDHN (standard connection), see Fig. 2. Since the return flow of the sub-LTDHN is cooled more than the return flow of the high-temperature consumers, the temperature of the HTDHN return flow is already reduced to a certain extent in the reference scenario.

The following are brief descriptions of the technical assessment cases:

2. Changing the HTDHN return temperature

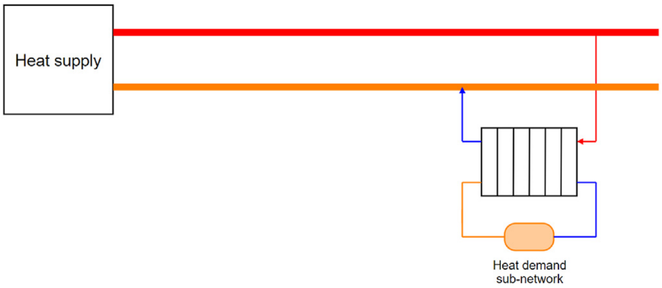


Fig. 2. Schematic of the connection for the reference case ('standard' connection to the supply pipeline).

The temperature of the return flow of the HTDHN directly affects the return temperature decrease that can be achieved. If the return flow temperature is lower than the necessary supply temperature of the sub-LTDHN, mixing of the supply pipe is required to maintain the temperature level. In that case, the achievable HTDHN return temperature reduction decreases. To evaluate this case, the return temperature of the HTDHN was varied between 50 °C and 70 °C, while the other network parameters were fixed.

3. Variation of connection point of the sub-LTDHN to the HTDHN

The location of the connection point of the sub-LTDHN directly affects the available return mass flow. It can be expected that at remote locations in the network, the mass flow is only a fraction of the available mass flow near the heat generators. In this case, the available mass flow may not be sufficient to supply the heat demand from the sub-LTDHN and mixing from the supply pipe is required. Therefore, the amount of mixing from the supply pipe depends on the location of the connection point. The variation of the connection point is calculated by varying the locally available return mass flow of the HTDHN ($\dot{m}_{ret,P,local}$).

2.2.2. *Network parameters*

The network parameters for the technical assessment are example values based on annual averages for the HTDHN of a Nordic city with a new residential area with the sub-LTDHN:

- Existing HTDHN with high temperature demand
  - Supply/return temperature: 100 °C/70 °C
  - Mass flow: 550 kg/s
- Sub-LTDHN with low temperature demand
  - Supply temperature: 65 °C/60 °C/55 °C
  - Return temperature: 40 °C/35 °C/30 °C
  - Mass flow: 15 kg/s
  - Connection point to the HTDHN: 10% of total mass flow available

2.2.3. *Economic assessment*

Based on the key indicator of return temperature reduction from the static technical assessment, the heat supplied to the network and data on the economic effect of reducing system temperatures, an economic assessment was performed focusing on improving the efficiency of heat supply technologies [18]. Since the efficiency of many heat supply technologies increases as the return temperature decreases, the cost of heat produced will be reduced.

To indicate monetary savings, the reference case of the technical assessment was chosen as the baseline and compared with the cascading case. Thus, the return temperature reduction for economic assessment was calculated as the difference in the return temperatures of both cases. In this case, only the advantages of the cascading connection were assessed, while ensuring that the total heat delivered to the network was the same in both cases. The savings associated with the network itself (higher capacity, lower pumping requirements, and lower loss) were not considered. Since the achievable savings can be higher considering the impact on the network, this calculation can be regarded as a lower limit for possible savings. In addition, the economic assessment does not cover the necessary investment costs for connecting the sub-LTDHN and the required infrastructure (i.e. substation with supply mixing).

The calculation is performed according to the formula shown in Equation (10).

$$Savings\left[\frac{€}{a}\right] = \sum_i CRG_i * E_i * \left(T_{ret,cascade} - T_{ret,reference}\right) \tag{10}$$

where CRG_i and E_i are the cost reduction gradient and the annual heat production for individual heat sources, respectively; $T_{ret,cascade}$ is the return temperature of the cascading connection and $T_{ret,reference}$ is the return temperature of the standard connection.

Since information on the DHN supply structure is necessary for the calculation, the economic assessment was conducted using a case study based on the DHN of a Nordic city. To do this, monthly data for 2019 on network parameters were obtained from the DH supplier. In addition, savings were also calculated for a hypothetical future supply mix that is mainly dependent on renewable sources.

Fig. 3 shows the two considered heat supply mixes in the HTDHN. The DHN's current supply mix is dominated by waste incineration plants and supplemented by various heat-only boilers. Here, the effect of DH system temperature reduction is very insignificant. Thus, a hypothetical future supply mix corresponding to a largely decarbonised heating network using alternative heat sources without combustion processes was also considered. Here, most of the heat is provided by excess heat sources and supplemented by heat pumps. In summer, small amounts of solar thermal energy are integrated, while the supply gap in winter is covered by CHPs.

2.3. Examination of operational dynamics

The second part examines the operational dynamics of a DHN with a cascaded sub-LTDHN. The system was modelled using the Dymola (Dynamic Modelling Laboratory) dynamic simulation software and the Modelica object-oriented modelling language with components from the existing *DisHeatLib* [20] and IBPSA [21] libraries. Compared to static analysis, this analysis considers heat loss, pressure loss and transfer efficiency of heat exchangers, resulting in a realistic simulation of a cascading substation. The focus of the analysis is on off-design cases representing certain boundary conditions associated with the barriers mentioned above and their impact on the system. Therefore, the behaviour of the system is studied under dynamic changes in input parameters, revealing issues that could not be addressed using static modelling (e.g. flow reversals). Since the results are evaluated at the substation level, the various HTDHN designs are not considered.

2.3.1. Fluctuating return temperatures

The return temperature of the HTDHN rarely matches the design conditions of a cascading substation, as they naturally vary due to load changes or weather conditions. While higher return temperatures are not expected to affect the cascading substation, return temperatures below the design temperature may result in an undersupply of the connected sub-LTDHN.

1. Fluctuatinsg mass flows

The amount of useable heat in the return pipeline of the HTDHN depends significantly on the currently available mass flow in the return pipeline at the connection point of the cascading substation. High return mass flows compared to the nominal values of the cascading substation are preferable. However, return mass flows in many DHNs show high seasonal, daily and hourly variation due to varying loading conditions. Also, the location in the HTDHN strongly affects the available return mass flows, for example, higher mass flows can be expected near heat generators and low mass flows can be expected at the end of feeders or at remote network locations. In the event that the return mass flow at the connection point is low during high demand in the sub-LTDHN, supply cannot be guaranteed by using the return pipeline alone.

Case 1. (return temperature variation): The first case examines the behaviour of the cascading substation in the context of fluctuating return temperatures in the HTDHN. This can affect the ability to supply the connected sub-LTDHN if the return temperature drops below the required supply temperature of the sub-LTDHN. In this case, the supply pipeline connection will be activated as a backup to ensure supply.

In the specific example, the return temperature is varied using a trapezoid signal. Thus, the return temperature at the cascading connection varies + - 15 °C around the nominal/design return temperature of 70 °C. The mass flow at the connection point and the heat load of the sub-LTDHN do not change.

Case 2. (return mass flow variation): The second case examines

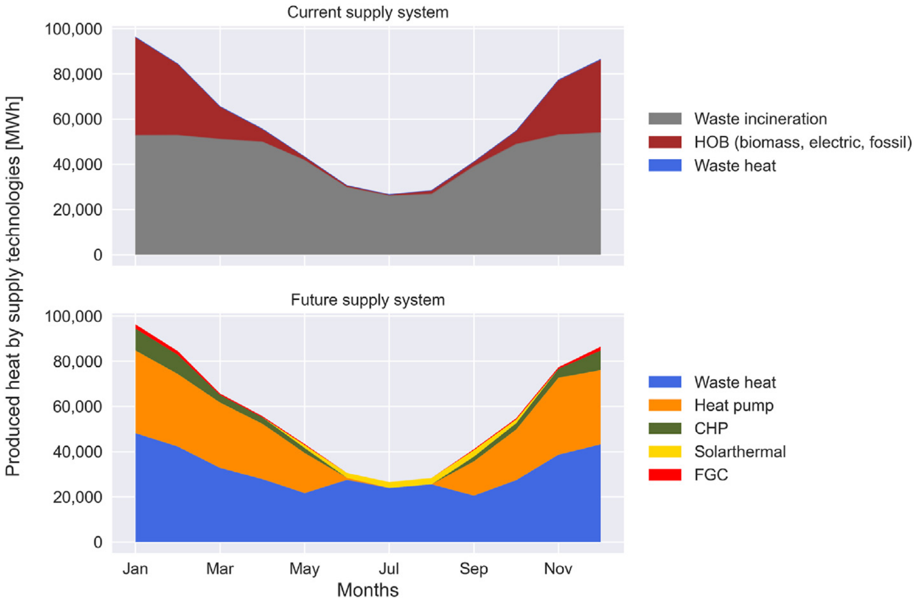


Fig. 3. Current and possible future heat supply structures for the case study.

the influence of variations in the return mass flow. While high return mass flows do not negatively affect the operation of a cascading substation, too low mass flows can lead to an undersupply of the sub-LTDHN. Again, the supply pipeline backup connection can be used during these times to ensure supply.

In this case, the mass flow at high-temperature heat demand changes according to a trapezoidal function within the range from 10% to 100% of its nominal value. The heat load of the sub-LTDHN and the return temperature of the HTDHN are not varied. Scheme of the setup of both cases can be seen in Fig. 4.

2.3.2. Network parameters

A small sample network was used to study the results of various boundary conditions in the network, see Figure. The network parameters used for this analysis are as follows:

- HTDHN:
  - o Supply/return temperature: 90 °C/70 °C
  - o Pipe length: 2 × 500 m, diameter: 80 mm
  - o Mass flow demand: 5 kg/s
- Sub-LTDHN:
  - o Supply/return temperature: 60 °C/30 °C
  - o Heat demand: 100 kW

3. Results and discussion

This section describes the results of the evaluation of technical barriers, the techno-economic analysis (technical and economic results are presented independently), and the results of the dynamic operation of the sub-LTDHN connected to the HTDHN.

3.1. Results of technical barrier rating

The results of questions related to technical barriers can be seen in Fig. 5.

Below is an analysis of technical barriers based on the questionnaire and other sources. The barrier rating is given in brackets.

3.1.1. Lack of suitable locations for the installation of a sub-LTDHN (3.12)

This barrier is related to the feasibility conditions. As mentioned above, the energy cascade option allows low-temperature district heating areas to be connected to a HTDHN. According to the survey, this barrier was often referred to as “slightly important’. This could be because there usually are locations where sub-LTDHNs can be installed. This barrier has been mentioned in various studies. For example [14], states that regardless of the type of building and year of construction, property developers often install standard heating systems (mostly radiators) in their buildings, implying that districts are not ready to be connected to LTDHNs.

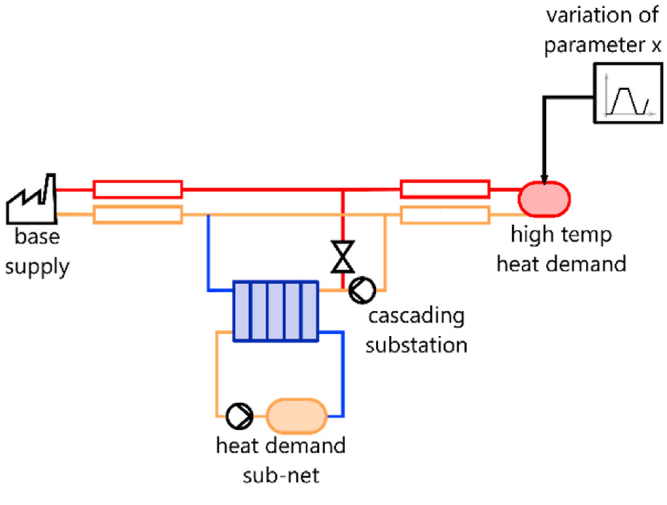


Fig. 4. Schematic of the setup of x variation of HTDHN (x = varied return temperature/return mass flow).

3.1.2. Low return temperature in the HTDHN (3.06)

According to the survey results, this barrier has a rather low rating, which could be because the vast majority of district heating companies supply heat via HTDHN, in which case the return temperature is quite high. Furthermore, the configuration of the energy cascade option allows the use of the supply pipeline if necessary. According to Ref. [17], too low a temperature in the return pipe can lead to Legionella problems and a situation where low-temperature DH consumers are not supplied sufficiently. In this case, a shortcut connection/thermostatic injection valve from the primary supply pipeline serving as a ‘top-up’ for the system can be a solution.

3.1.3. The necessity of locally boosting supply temperature (3.38)

According to the respondents, this barrier is of paramount importance. Considering that the HTDHN supply and return temperatures will be lower in the coming years, due to system renovation and the use of low-grade heat sources, it will be necessary to increase the sub-LTDHN supply temperature. Especially in summer, when the HTDHN return temperature is 40 °C or lower, it becomes necessary to boost temperature for domestic hot water. There are two ways to boost the supply temperature of a sub-LTDHN. Local renewable low-grade heat sources are one of the options, and this option is usually available during the summer (solar heating, seawater and river low-grade heat). But these options are not always accessible at sub-LTDHN locations. The other option is to take heat from the supply pipeline.

3.1.4. Mass flow barriers: limited mass flow rate and hydraulic issues (3.14)

These barriers are considered very important (ranked 3rd and 4th, respectively). Survey respondents and expert workshop participants noted that it is very important to have a sufficient mass flow rate in the HTDHN at the location of the sub-LTDHN. An additional pump is usually required to integrate cascade solution without hydraulic issues.

3.1.5. Multiple heat sources (2.99)

Multiple heat sources in an HTDHN can be considered a barrier because the mass flow rate and return temperature in HTDHN are likely to be lower in some cases. Usually, when there is one heat sources providing heat to the large HTDHN, supply and return temperatures should be higher. In addition, the positive effect of HTDHN return temperature reduction is not so significant, when there are multiple heat sources, comparing with one heat source (CHP or boiler with flue gas conditioning). According to the survey, this barrier has the lowest priority.

3.1.6. More complex regulation (3.28)

This barrier has been described in the scientific literature [11,12,17]. The barrier is regarded as highly important (ranked 2nd) by the respondents. The number of actors involved will increase the complexity of regulation and design. Heat will be supplied from the HTDHN to the sub-LTDHN both through the return line and, in some cases, through the supply line. Issues related to flow and pressure may occur. There are regulation solutions for effective system regulation, including, for example, a return valve and a temperature sensor in the main supply pipeline to the LTDHN,

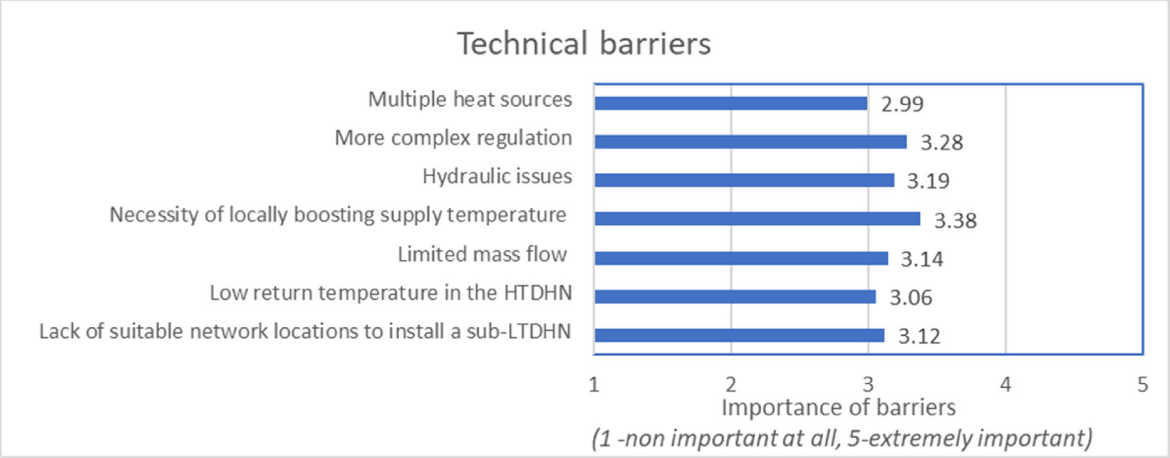


Fig. 5. Results of questions related to technical barriers.

according to Ref. [11]. System digitalisation and heat generation and consumption prediction will help to overcome these difficulties.

As can be seen from the above analysis, most of the technical barriers are related to the mass flow rate and return temperature of the HTDHN. This means that an additional techno-economic analysis should be conducted to provide further information on the solution's potential and to assess the techno-economic impact of cascading sub-LTDHN on the return pipe of an existing HTDHN.

3.2. Results of the techno-economic analysis

3.2.1. Variation of HTDHN return temperature

Fig. 6a depicts the decrease in the temperature of the HTDHN return flow depending on the return temperature of the HTDHN. The temperature decrease shows a linear increase until the HTDHN return temperature reaches the supply temperature of the sub-LTDHN. A further increase in the return temperature does not affect the achievable temperature reduction. The largest decrease from the reference case is achieved at the end of the linear increase, reaching 0.44 K, 0.42 K and 0.40 K for the sub-LTDHNs with supply temperatures of 55 °C, 60 °C and 65 °C, respectively.

Fig. 6b shows the local decrease in the return temperature in the specific branch of the network to which the sub-LTDHN is connected. Since less mixing from the supply pipe is required as the return temperature of the HTDHN increases, the temperature drop increases until the return temperature reaches the supply temperature of the sub-LTDHN. Due to the limited amount of mass flow available within this particular branch, the achievable temperature reduction is more significant than that of the total network.

The amount of mixing from the supply pipe is depicted as share of the supplied heat in c. For a given return temperature of 55 °C, the differences between the three sub-LTDHN temperature levels are obvious. While no mixing from the supply pipe is required for the sub-LTDHN with a supply temperature of 55 °C, almost 30% is required for the sub-LTDHN with a supply temperature of 60 °C, and over 50% for the sub-LTDHN with a supply temperature of 65 °C. Thus, the lower system temperatures in the sub-LTDHN are crucial, since they significantly affect the amount of heat that can be extracted from the return pipeline and, therefore, the return temperature reduction.

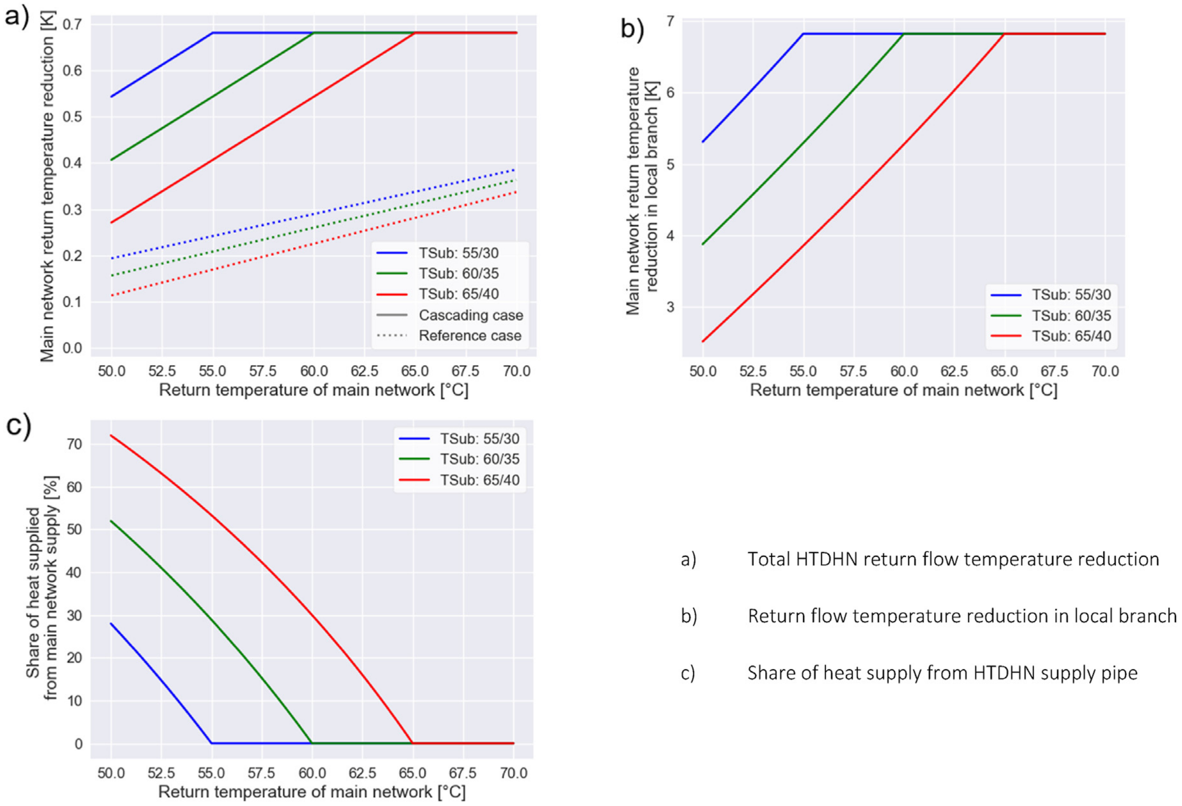
3.2.2. Variation of connection point of the sub-LTDHN to the HTDHN

Fig. 7a depicts the decrease in the HTDHN return temperature depending on the connection point of the sub-LTDHN. For very low available mass flows, the heat extracted is not enough to meet the demand of the sub-LTDHN. Therefore, mixing from the supply is required, see Figure c. As the percentage of available mass flow increases, the amount of mixing from the supply decreases, and the total achievable return temperature reduction increases. Since the HTDHN return temperature is higher than the required supply temperature of the sub-LTDHN, the heat demand can be met solely via the return pipeline, if sufficient mass flow is available. In this case, the resulting overall return temperature reduction is constant, since further increase in the available mass flow will not affect the extracted amount of heat. The required mass flow rate to supply the sub-LTDHN depends on the temperature level of the sub-LTDHN. As the temperature difference between the HTDHN return and the sub-LTDHN return increases, the extractable heat from the return pipeline also increases, resulting in less mass flow needed to supply the heat demand. Regarding the reference case, the connection point has no influence on the return temperature reduction, as no restrictions on the available flow from the supply pipe were set. The maximum achievable reduction of the return temperature compared to the reference case is 0.30 K, 0.32 K and 0.34 K for the sub-LTDHNs with supply temperatures of 55 °C, 60 °C and 65 °C, respectively.

A local decrease in the return temperature in a specific branch of the network is shown in Figure b. At low percentages, all available return flow is cooled down to the maximum sub-LTDHN return temperature. Once the available mass flow exceeds the amount needed to meet the heat demand of the sub-LTDHN, the temperature drop is reduced because not all of the mass flow is utilised.

3.2.3. Case study including economic assessment

The case study is based on the DHN of a Nordic city with an HTDHN and a newly planned residential area with a sub-LTDHN. Table 3 shows the monthly network parameters for this system, obtained by averaging the hourly values for each month. Because the calculation was based on a static model, the data was adapted to the constraints outlined in the Methods section. To generate data for a simplified linear network with a single central heat supplier, the amount of heat delivered to the network and the supply/return temperature were used to calculate the total mass flow in the simplified HTDHN. As no mean system temperature levels for the

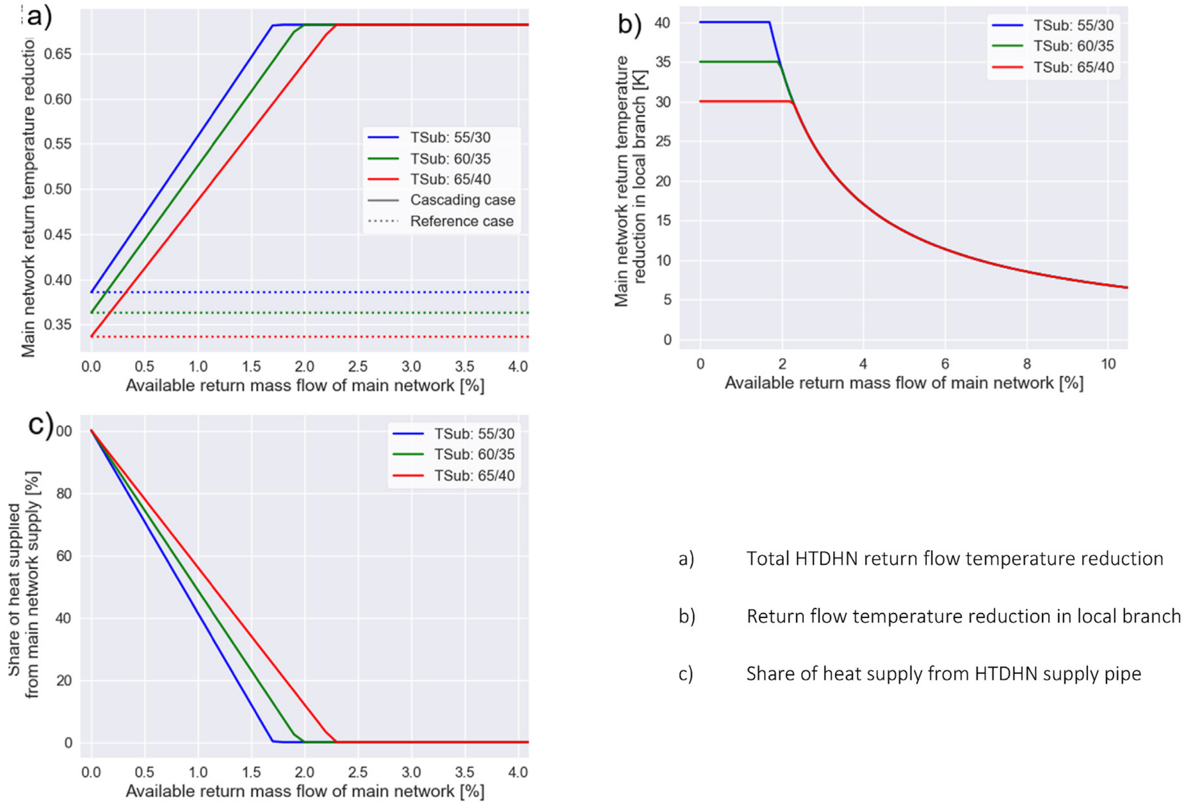


a) Total HTDHN return flow temperature reduction

b) Return flow temperature reduction in local branch

c) Share of heat supply from HTDHN supply pipe

Fig. 6. Impact of the variation of the HTDHN return temperature on the total return temperature reduction, the local return temperature reduction, and the share of heat supply from the supply pipe.



a) Total HTDHN return flow temperature reduction

b) Return flow temperature reduction in local branch

c) Share of heat supply from HTDHN supply pipe

Fig. 7. Impact of the change in the connection point on the total return temperature reduction, the local return temperature reduction, and the share of heat supply from the supply pipe.

Table 3
Input data for the case study of an HTDHN and a possible sub-LTDHN.

Month	Supply Temp. [°C]	Return Temp. [°C]	Mass flow [kg/s]	Mass flow at connection point [kg/s]	Supply Temp. [°C]	Return Temp. [°C]	Mass flow [kg/s]
	HTDHN				Sub-LTDHN (supply temperature		
Jan.	96.01	68.75	1113.47	31.49	60	35	19.36
Feb.	93.26	65.14	1047.01	22.65			19.81
Mar.	99.93	66.56	616.02	31.55			18.36
Apr.	105.78	71.68	530.34	26.84			14.04
May	108.07	70.38	361.10	29.29			10.46
Jun.	105.82	77.45	350.06	18.27			7.46
Jul.	106.44	77.08	284.42	20.11			6.01
Aug.	105.71	77.20	313.24	21.28			6.16
Sep.	106.97	76.04	432.98	28.51			7.98
Oct.	104.37	71.74	527.63	26.29			12.54
Nov.	99.35	65.05	733.29	18.91			17.01
Dec.	106.08	59.98	589.31	22.92			20.05

HTDHN were available, the temperatures within a specific network branch near the location of the sub-LTDHN were used as input data for the entire HTDHN. This can lead to an overestimation of the mass flow rates in the HTDHN, since the actual supply and return temperatures throughout the HTDHN potentially have a larger spread. The mass flow at the connection point of the sub-LTDHN was assumed as equal to the mass flow in the network branch near the location of the sub-LTDHN. Heat demand data for the sub-LTDHN was generated using a statistical load profile generator [22]. The temperatures within the sub-LTDHN are fixed at 60 °C/35 °C throughout the year. During the summer, increased sub-LTDHN return temperatures may lessen the influence on the overall network return temperature reduction. In addition, a 60 °C supply temperature in sub-LTDHN can lead to Legionella problems for domestic hot water preparation. However, this obstacle is inherent to all LTDHNs and is not within the scope of this study.

The effect of cascading the sub-LTDHN was analysed using a static model in comparison to the reference case, in which the sub-LTDHN is fed directly from the supply pipe. The heat demand of the sub-LTDHN can be supplied from the return pipeline alone in all months except December, when 0.1% of the delivered heat is supplied from the supply pipe to reach the required supply temperature of the sub-LTDHN. The reason for this is the high return temperature of the HTDHN, which for most of the year is above the required supply temperature of the sub-LTDHN. Only 36% of the annual heat demand of an existing sub-LTDHN (supply temperature 55 °C, return temperature 40 °C) was supplied by the HTDHN return flow, according to a related study, because the average annual HTDHN return temperature was only 48 °C, which was below the fixed supply temperature of the sub-LTDHN [23]. Similar results were obtained during the analysis of a potential sub-LTDHN in Estonia, where the HTDHN return flow with an average temperature of 50 °C provided 25% of the total heat demand of the sub-LTDHN (supply temperature 65 °C, return temperature 35 °C) [9].

The resulting decrease in the return temperature for each month is shown in Fig. 8. Compared to the reference case, a return temperature reduction between 0.20 K and 0.55 K was achieved. Particularly high reductions compared to the reference case were observed from March to May and in December. The reason for this is the higher ratio of sub-LTDHN heat demand to mass flow throughout the network during these months. This results in a larger percentage of the total return flow being used, resulting in larger reductions .

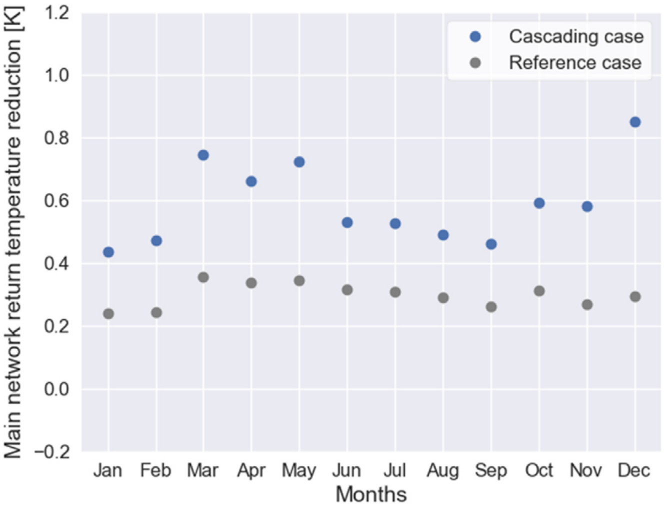


Fig. 8. Total return temperature reduction in the case study.

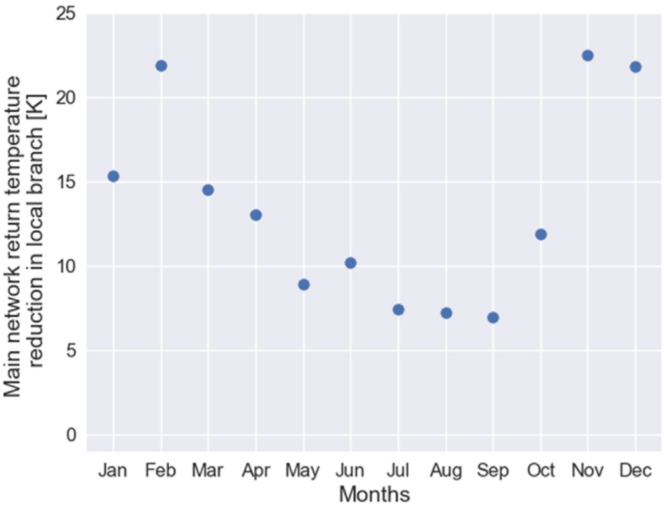


Fig. 9. Local return temperature reduction in network branch in the case study.

The local temperature reduction in the HTDHN branch to which the sub-LTDHN is connected is shown in Fig. 9. This depends on the ratio of the sub-LTDHN heat demand to the available return mass flow in the branch. Therefore, a significant decrease of more than 20 K occurs in February, November and December, when this ratio is especially high. During the summer months, when the heat demand of the sub-LTDHN is low, the achievable reduction is much smaller.

The aggregated annual savings for individual heat supply

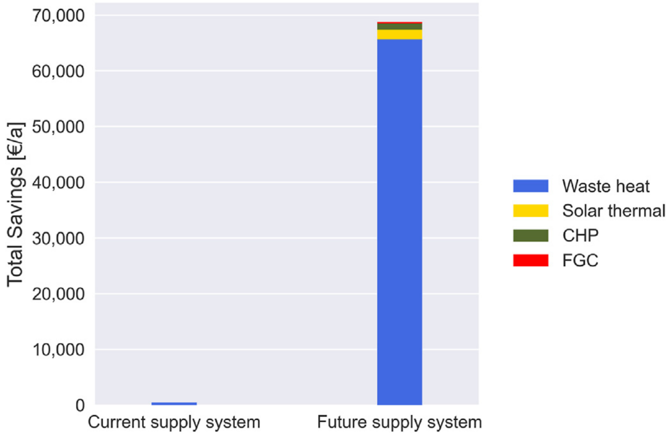


Fig. 10. Cost reductions due to reduced network return temperatures in the case study.

technologies are shown in Fig. 10. With the current supply mix, very little savings are possible, as waste incineration plants (without cogeneration) and heat-only boilers (without flue gas condensation) cannot benefit from lower return temperatures [18]. In contrast, for a similarly sized sub-LTDHN cascaded into an HTDHN that is supplied by CHP plants with flue gas condensation, savings for the mentioned heat supply technologies amounted to €71,500/a [9].

For a hypothetical future supply mix scenario, significant savings comparable to Ref. [9] can be achieved, mainly due to the impact of excess heat sources. Heat pump savings are not included in Fig. 3, because this technology does not benefit from reduced return temperatures due to the fact that the heat pump uses ambient heat to raise the return flow to the temperature level of the supply.

3.3. Operational dynamics results

3.3.1. Fluctuating return temperatures

Fig. 11 shows the resulting temperatures at the cascading connection for the case of fluctuating return temperatures. The assumed trapezoidal change in the return temperature of the HTDHN is clearly visible. The supply temperature set-point of 60 °C for the sub-LTDHN can be kept constant even when the return temperature of the HTDHN drops below 60 °C. Although the return temperature of the sub-LTDHN is constant, the return temperature of the cascading connection varies. This is due to the higher HTDHN return temperature at this time.

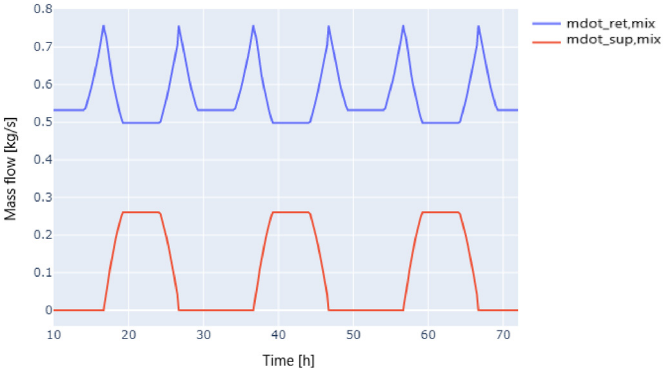


Fig. 12. Resulting mass flows for mixing supply and return at cascading connection for fluctuating return temperatures in the HTDHN (mdot_ret, mix = mixing mass flow return pipeline, mdot_sup, mix = mixing mass flow supply pipeline).

Fig. 12 shows the resulting mass flows from the HTDHN return and supply pipelines. During periods of too low return temperatures, i.e. not high enough to reach the supply temperature set-point of the sub-LTDHN, the substation starts to increase the use of return water from the HTDHN until the temperature is no longer sufficient. Then it starts mixing from the supply pipeline to reach the temperature set-point, and the amount of return water used for mixing is reduced to the point where the return temperature begins to rise again. A backup supply connection allows meeting the demand even during periods of low return temperatures in the HTDHN.

3.3.2. Fluctuating mass flows

Fig. 13 shows the resulting temperatures at the cascading substation for the case of fluctuating mass flows in the HTDHN. The supply of the sub-LTDHN is satisfied because the supply temperature is equal to the setpoint. Due to the low mass flow in the HTDHN during certain periods, the return temperature of the HTDHN detected by the cascade substation is significantly lower its nominal value of 70 °C. This is directly related to the multiple use of the return water by the cascading substation. Due to the small volumes of return flow in the HTDHN at certain points in time, the return water feed of the cascade connection into the main return pipeline after use (temperature *T_ret, cascade connection*) can have

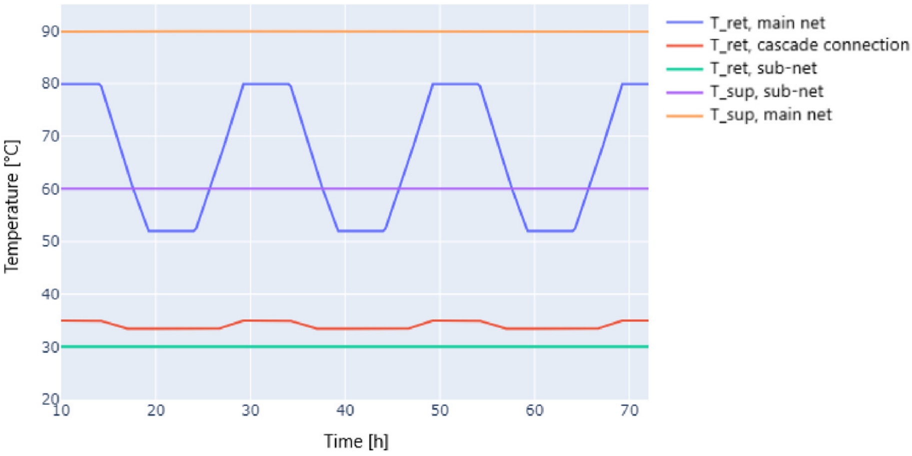


Fig. 11. Resulting temperatures at cascading connection for fluctuating return temperatures in the HTDHN (T_ret = return temperature, T_sup = supply temperature).

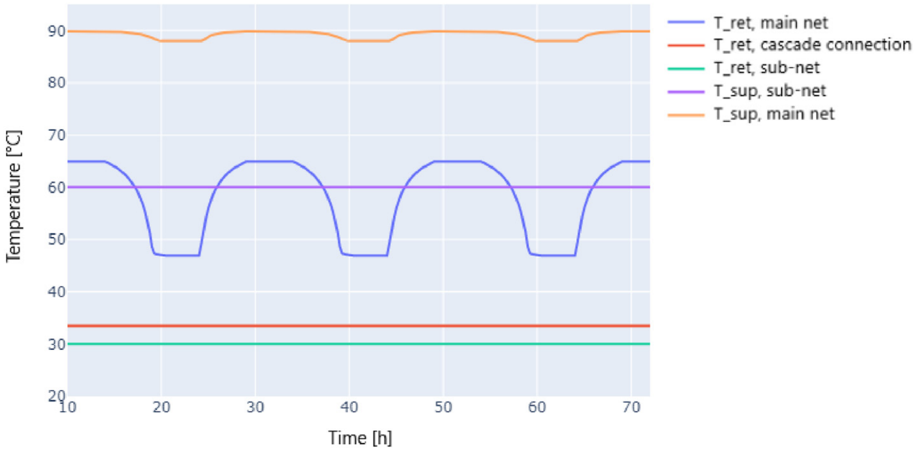


Fig. 13. Resulting temperatures at cascading connection for fluctuating mass flows in the HTDHN (Turret = return temperature, T_sup = supply temperature).

a higher pressure than the return flow of the HTDHN that is used by the cascade substation (temperature *T_ret, main net*), leading to flow reversal. Thus, the return water gradually cools down and the incoming return water from the high-temperature demand is not able to compensate for this heat loss. The HTDHN supply temperature in terms of the cascade is slightly reduced at times of low mass flow rates at the high-temperature consumer due to lower velocities in the piping and, as a result, higher heat loss.

Fig. 14 shows the return mass flow in the HTDHN and the resulting mass flows from the HTDHN return and supply pipelines used for mixing at the cascading substation. During periods of too low return temperatures, i.e. not high enough to reach the supply temperature setpoint of the sub-LTDHN, the substation starts mixing from the supply pipeline. This allows the demand to be met even during periods of low return temperatures in the HTDHN.

4. Conclusion

Sub-LTDHNs connected to the return pipeline of the existing HTDHN, so-called cascading, allow the utilisation of low-grade heat in the network, reduce heat loss and increase energy generation efficiency due to overall reduced network temperatures and thus can be considered an important opportunity for DH transition towards 4GDH. Furthermore, cascading allows the DHN transport capacity to be increased for new areas without the need for new transmission lines.

Although DHN operators are familiar with sub-LTDHNs, they are hardly used at the moment. Despite the potential benefits of cascading, the technical barriers, operational dynamics and potential cost savings have yet to be thoroughly considered.

The most significant technical barriers to cascading identified in this study are related to possible low return temperatures and mass flow limitations in the HTDHN, which necessitate boosting the supply temperature locally using the mass flow from the supply line, as well as the complexity of the system control. To compensate for the undersupply from the HTDHN return line, suitable local boosting solutions include local backup supply units and demand response options in the sub-LTDHN itself. However, these options will dramatically increase investment costs.

A techno-economic analysis was performed using various network parameters to explore cascading solutions. For a more detailed analysis, a case study was carried out based on data for a planned residential area in a Nordic city.

First, a static analysis was conducted to give an overview of the theoretical possibilities of cascading. Monthly analysis shows that the area is in theory suitable for cascading with the existing

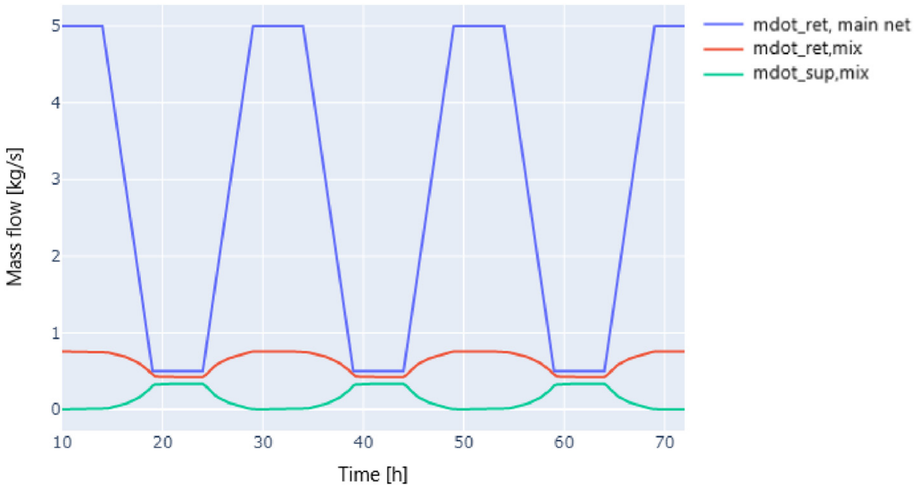


Fig. 14. Resulting mass flows for mixing supply and return at cascading connection for fluctuating mass flows in the HTDHN (mdot_ret, main net = return mass flow HTDHN, mdot_ret, mix = mixing mass flow return pipeline, mdot_sup, mix = mixing mass flow supply pipeline).

network. Since the HTDHN's current supply structure is dominated by heat-only boilers that do not benefit from lower return temperatures, the estimated cost savings due to lower return temperatures are small. Cost savings resulting from reduced heat loss were not considered. The developed scenario of a hypothetical future supply system with minimum use of combustion technologies has shown that there are significant savings that can offset the potentially higher costs of the cascading connection.

Second, the operational dynamics of a DHN with a cascading sub-LTDHN was studied. Key dynamic parameters such as mass flow and return temperature of the HTDHN vary and their impact on supplying the heat demand for the sub-LTDHN has been investigated. The scenarios discussed illustrate the technical difficulties that may arise when choosing to supply sub-LTDHNs via the return pipeline of an HTDHN. These technical difficulties must be considered at the design stage, since they are mainly caused by the dynamics of mass flow and temperature at the cascade connection point in the HTDHN.

The results show that the sub-LTDHN connection point in the overall DH network is an important aspect as it determines the volume of return flow available. If the local return temperature or the available mass flow is too low, mixing from the supply pipe is required to provide the necessary amount of heat.

However, locations near heat generation units with higher return mass flows, limit the impact of reduced return temperatures. Heat loss can only be reduced marginally, as the time the water stays in the pipeline is short until it reaches the heat generation units, and increased network capacity may not be as valuable close to heat generation units compared to remote sections of the network. This leads to a compromise on the optimal connection point. Benefits such as reduced network losses and increased capacity are more valuable if the sub-LTDHN is connected far from heat generation units. However, connecting the sub-LTDHN closer to the heat generation units ensures sufficient return mass flow and, therefore, allows for a potentially larger reduction in the overall return temperature.

Thus, the limited number of suitable locations for cascading connections is identified as a key barrier to using cascading as a scalable solution to reduce the return temperature in existing networks. Validation of the obtained operational dynamics results with a practical example is currently not possible, but is very important in advancing practice-oriented analysis.

In general, sub-LTDHN integration will require significant technical efforts, however, they will contribute to the transition of HTDHNs to LTDHNS and eventually to 4GDH. Even if sub-LTDHNs are not generally feasible and reasonable in all locations, they may be a scalable option for lowering the return temperature in network branches near heat generation units where implementation makes sense for capacity and cost reasons. Especially in residential areas (new or existing) with low energy house standards.

One of the most significant applications of cascading will be network branches that include buildings with limited options for reducing their return temperatures. These limitations could be of economic nature (e.g. high retrofitting costs) or of regulative nature (e.g. ownership of buildings and substation, as well as options for accessing the installations). In this case, cascading may be the only way to reduce the return temperature locally.

Reducing the return temperature through sub-LTDHN options is beneficial mainly when non-combustion heat sources are used, such as geothermal heat [18]. However, many DH networks are dominated by high-temperature supply units such as CHP plants and heat-only boilers, where lower system temperatures have little positive effect. Very often, connected buildings are also designed for high temperatures, and lowering these temperatures requires a significant investment into the building's heating system. In turn, the incentives to lower the system temperature are insignificant. But without temperature reduction, the economic performance of local low-temperature renewable sources will be poor. This results in an unfavourable cost-benefit ratio and thus in a lock-in effect on the existing high-temperature heating system. This situation maintains the dominance of high-temperature supply units. Cascading can be a relatively simple solution for lowering the system temperatures, since it can be applied to the network section without having to modify the building's heating system. Thus, cascading can be the starting point for the transition of the entire network to the 4th generation system.

In this context, the analysis of possible barriers and applications of cascading solutions can serve as a knowledge base and thus as a trigger for DHN operators to investigate their networks for their potential to incorporate sub-LTDHNs. Potential future efforts to promote cascading should include a citywide analysis and optimisation of the various cascading solutions and their interaction with each other and the various supply units, as well as an implementation strategy. These solutions will also need to be demonstrated in action in suitable locations in the future, in collaboration with DH operators, investors, and sub-LTDHN operators.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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