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Potential for supply temperature reduction of existing district heating substations

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ABSTRACT

Reducing operating temperatures is a crucial goal for transforming district heating networks into sustainable systems as it allows the integration of low exergy heat (e.g. renewable, waste heat). Many criticalities arise when reducing operating temperatures in existing networks that are not designed to operate in these conditions. The criticalities occur at different levels: in the building, in the thermal substations, in the pipelines and in the production plants. In this paper, the reduction of supply temperature in existing district heating substations is analyzed. A methodology including a model of the thermal substation and a data analysis software is developed to estimate the potential temperature reduction that could be applied to existing substations. The application of the model to an existing large-scale district heating network in Northern Italy shows that all the analyzed substations are currently able to shift their operation from 120 °C to 104 °C, and that district heating supply temperatures around 90 °C can be realistically achieved with few improvements on the system.

1. Introduction

During recent times, District Heating (DH) technology is establishing itself as the most cost-effective solution to provide space-heating and domestic hot water to buildings located in dense urban areas, being able to combine competitive costs with low environmental impact [1].

The first commercial DH solutions appeared in the late 19th century in cities like Lockport and New York [2]. In Europe, it was introduced in the 1920s in Germany [3]. Since then, a lot has changed in DH technology and nowadays European countries are the leading users of DH and the key players in the technology transition [4]. This transition will make DH a leading technology of the future urban energy infrastructure, as it is expected to account for 5% of total final energy use by 2050, with 77% of this share being provided by renewable energy sources [5].

The undergoing transition to the so-called 4th Generation District Heating [6] will require the systems to have new characteristics. Among them, the ability to operate with lower operating temperatures assumes a central role [7], since it is essential for the integration of renewables [8] and thus represents a fundamental goal for the decarbonization of the technology. For this reason, the scientific literature has extensively addressed this topic [9], focusing on the design [10], advantages and possible evolution of this technology [11,12].

Several advantages of using Low-Temperature District Heating (LTDH) can be found both for the heat supply, the heat distribution, and the heat utilization. On the supply side, LTDH can contribute to increase the efficiency of heat production both from conventional technologies (e.g. combined heat and power, heat pumps) and renewable energy sources (e.g. waste incineration, waste heat, biomass fuels, geothermal heat, solar heat) [6,10,13–15] and it enables the integration of small scale heating prosumers [10,16]. The benefits are not only related to the heating sector but can also extend to other sectors, like the power or gas sectors, as LTDH facilitate the use of conversion technologies [17,18] in a multi-energy system perspective [19–21]. Considering the heat distribution, the benefits of LTDH are mainly related to the lower heat losses along the network: Li et al. [22] reported a potential reduction in the heat losses up to 75% in the case of well-designed DH networks with respect to current systems. Minor advantages are also related to the possibility to use plastic pipes, the prevention of evaporation risks and the reduction of thermal stresses in the pipes [14,23]. At the distribution level, the reduction in supply temperature also leads to a main drawback associated with an increase in pumping costs. Finally, the advantages for the consumption side (i.e. the DH customers) are represented by the increased match between the temperature levels of heating demand and supply, which contributes to reduce the energy/exergy losses of the system [24,25]. Another potential benefit of LTDH for consumers is a possible price reduction due to efficiency improvements in the system

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[10] or, in the case of prosumers, due to the possibility of selling surplus heat to the heating network.

Østergaard and Svendsen [26] evaluated the costs and benefits of the transition to low temperatures for the Danish energy system, proving the feasibility of preparing existing buildings for low temperature DH. Schmidt et al. [27] analyzed 15 case studies of successful implementation of LTDH. Another work by Werner [28] discussed the suitability of different configurations adopted in low-temperature networks. Nord et al. [29] analyzed the challenges for low-temperature district heating in Norway and evaluated the competitiveness of lower temperatures depending on the heat density, per unit area, by comparing the variation of heat losses and pumping energy. Their study proves that despite the decrease in competitiveness for areas with heat density lower than 1 MWh/m, the increase in pumping energy is low in comparison to the heat saved by reducing temperatures. A comprehensive review of the strategies adopted to reduce supply temperature in existing DH networks was developed by Guelpa et al. [30]. The IEA Technology Collaboration Programme on District Heating and Cooling has promoted several initiatives in addressing on this topic: within Annex X, a project [14] was devoted to identify the main advantages of LTDH; in Annex TS1 [31], the potential of LTDH as one of the most relevant solutions to achieve 100% renewable and greenhouse gas emission-free energy systems has been demonstrated. In a further project belonging to Annex XI [32], the specific issues of transitioning from high to low temperature networks were addressed; finally, Annex TS2 [33] was devoted to the definition of guidelines for the implementation of LTDH.

Despite the significant efforts, several technical and economic issues still need to be faced, especially in already existing infrastructures. Focusing on the technical issues, three major categories of barriers can be identified both at the heating equipment level (inside the building), at substation level, and at network level:

1. Concerning the heating equipment within the buildings (e.g. radiators), their size may be insufficient to meet the required heat demand at a lower supply temperature [34]. This can occur, for example, in the case of radiators with limited heat exchange area, which is not suitable for operation at much lower supply temperatures.
2. At substation level, the area of the heat exchanger may be insufficient to exchange the required heat when temperatures are reduced [30].
3. Finally, at network level, there are limitations related to the increase in the mass-flow rate needed to compensate for the decrease in the supply temperature at the substations [35]. In some cases, this increase can cause water congestion in some areas of the network [36].

Analyzing the literature, it turns out that investigations about supply temperature reduction in existing DH infrastructures are mainly related to limitations occurring at the building heating devices. Many of them have shown that it is possible to use low-temperature DH in existing buildings for most of the year. Hesaraki et al. [37] performed an experimental study in a climatic chamber test facility simulating an average multi-family building constructed between 1976 and 2005; the work has shown that thermal comfort can be achieved with a supply temperature of 45 °C using conventional radiators (and lower using other heat emitters). Nagy et al. [38] developed a methodology to determine the retrofit measures that are needed to sufficiently reduce the supply temperature of the heating system, and found that the current state of the analyzed building is already suitable for low temperature supply. Østergaard and Svendsen [39] focused on single-family houses in Denmark and showed that radiators are often over-dimensioned for the current heat demand.

Fewer efforts have been made to overcome the limitations on substation and network level. Cenian et al. [40] reported that these are both oversized on average by more than 2 times in the considered DH system in Poland, giving the possibility of implementing a supply temperature reduction from 121 °C to 109.8 °C. Especially in the case of large DH, these two problems need to be addressed in depth, using proper tools to describe the operation of the substations [41] and the thermo-fluid dynamics of the water circulating in the network [42,43] in order to quantify their limitations and potential. Thus, this has been set as the main goal for a further project financed by IEA-DHC within Annex XIII.

In this framework, this paper aims at developing a methodology to estimate the potential for supply temperature reduction associated with existing DH substations. Such an analysis is crucial since existing networks represent the largest share of the DH systems expected to be in operation in the next few years. This becomes even more important in large-scale systems, where there are several technical challenges, associated with both the large size of the systems and the huge amount of data to be handled, but also relevant opportunities in terms of the potential impact of the flow temperature reduction.

The main contributions of this paper can be summarized by the following points:

- To propose an operational model able to test in advance the behavior of thermal substations installed in the buildings when the network supply temperature is reduced.
- To suggest a methodology, including substation/building model and a data analysis software, which is able to determine the minimum supply temperature required by the substations in an existing large-scale DH system. The main idea is to use the operational model to test the limitations on temperature reduction associated with each substation and due to the building demand, size of the heat exchanger, temperatures on the heating system, etc.
- The application of the model on a large-scale DH network for which the specifications of the substations were not known in advance. Indeed, in order to test the proposed methodology and evaluate the potential for supply temperature reduction of a real case study, application to existing substations of a DH network located in Northern Italy is proposed.

2. Methodology

In this section, the proposed methodology to evaluate the potential for supply temperature reduction of existing DH substations is described. A schematic of the methodology is reported in Fig. 1; the model is composed by three main interconnected parts:

- The first step (block in the figure) consists of a substation model (detailed in Section 2.1) developed to replicate the operation of a

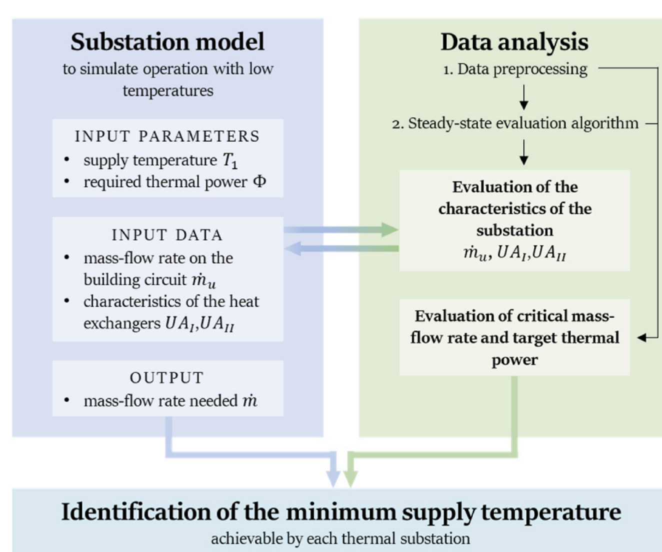

Fig. 1. Schematic of the methodology adopted in this work.

substation and of the building connected to it. This is done to test what the physical behavior of each substation would be if supplied with lower temperatures. The model also includes a simplified representation of the secondary-side of the building to ensure no change in thermal comfort, as specified in Section 2.1. The model also estimates the mass-flow rate required to provide sufficient thermal power to a building when operated at a given supply temperature.

- The second part consists of a data analysis software, which is developed in this paper to obtain some pieces of information that are often not available in DH networks and that are needed to reproduce the operation of the users and to evaluate the minimum supply temperature achievable. Specifically, the analysis proposed in this paper requires as input values: a) the mass-flow rate on the heating system circuit (secondary side); b) an estimation of the heat transfer coefficient; c) the area of the heat exchangers; d) the conditions that must be assured in terms of target thermal power; e) the maximum mass-flow rate on the network side that can be handled by the substation (primary side). Since these data are very often not available, especially in the case of large DH, a self-developed software is used to estimate these quantities on the basis of data collected during operation. In particular, the four temperatures at the substation (supply and return temperatures on both sides) and the DH circuit mass-flow rate are monitored during operation. These data are used in the data analysis software detailed in Section 2.2., which consists of dedicated algorithms (e.g. algorithm for the automatic identification of the steady-state operating conditions, assessment of the technical performance of the heat exchangers, identification of the critical mass-flow rate and the target thermal power as a function of the outdoor temperature) and represents the part of the model that requires the greatest computational effort.
- The last part of the model merges the substation model results and the data analysis results to identify the minimum supply temperature achievable by each substation analyzed, as shown in Section 2.3. Different supply temperatures are then considered in order to verify the statistics in terms of suitability.

The three parts described are all essential for the proposed model to work and be applicable to potential case studies. The implementation is carried out using MATLAB [44].

2.1. Model of the user (substation and building)

A simplified model is adopted to reproduce the physical behavior of the thermal substations and connected buildings. A schematic of the main elements used in this model is given in Fig. 2. The model simplifies the substation + building system into two heat exchangers:

- The first is the heat exchanger (*HX1*) of the thermal substation. It connects the district heating network (also called "primary circuit") to the building's heating circuit (i.e. "secondary circuit"). In this heat exchanger, a mass-flow rate $\dot{m}$ supplied by the district heating network, with an inlet temperature T_1, is used to provide a certain amount of heat to the building's heating circuit. The DH water is cooled down in the substation to an outlet temperature T_2.
- The second heat exchanger (*HX2*) is fictitious and it is equivalent to the set of all the heating devices in a building. It is used to represent the heat exchange between the heating circuit in the building and the indoor environment, whose temperature should be maintained as required by the end-users (i.e. the temperature profile during the day is assumed as a condition to be guaranteed). This approach is adopted because of the large number of heating devices in each building and due to the difficulty in obtaining specific data for individual devices. In addition, a compact model is easily applicable to large systems and is less dependent on measurement. In HX2 the total mass-flow rate of the building heating circuit $\dot{m}_u$ is processed. The inlet temperature of the hot side of the second heat exchanger T_3 is set by a control system, which adjusts it according to the set-point temperature $T_{3,set\ point}$. $T_{3,set\ point}$ is determined by a weather-dependent curve which depends on the external temperature T_{ext}. The mass-flow rate $\dot{m}_u$ is used to supply the required heat Φ to the internal spaces; the return temperature T_4 is a consequence of the operation of the heating devices. The internal rooms are modelled as one environment with constant temperature T_{indoor}.

The equations that are used to describe the system consist of the energy balances and the effectiveness-NTU method [45]:

1. The energy balance across the DH network side of HX1, Eq. (1);
2. The energy balance across the building side of HX2, Eq. (2);
3. The effectiveness-NTU relations for HX1, Eq. (3) and Eq. (5);
4. The effectiveness-NTU relations for HX2, Eq. (4) and Eq. (6).
5. The definitions of the heat capacity ratio ω and the number of transfer units *NTU* for the two heat exchangers, reported in Eqs. 7–10 (the expressions are written considering that a) the fluid circulating in both the circuits is the same and b) the mass-flow rate of the indoor-side of the second heat exchanger can be assumed to be infinite).

$$\Phi = \dot{m}\, c_p (T_1 - T_2) \tag{1}$$

$$\Phi = \dot{m}_u\, c_p (T_3 - T_4) \tag{2}$$

$$\Phi = \varepsilon_I\, \dot{m}\, c_p (T_1 - T_4) \tag{3}$$

$$\Phi = \varepsilon_{II}\ \ \dot{m}_u\, c_p (T_3 - T_{env}) \tag{4}$$

$$\varepsilon_I = \frac{1 - exp(-(1-\omega_I)NTU_I)}{1 - \omega_I\, exp(-(1-\omega_I)NTU_I)} \tag{5}$$

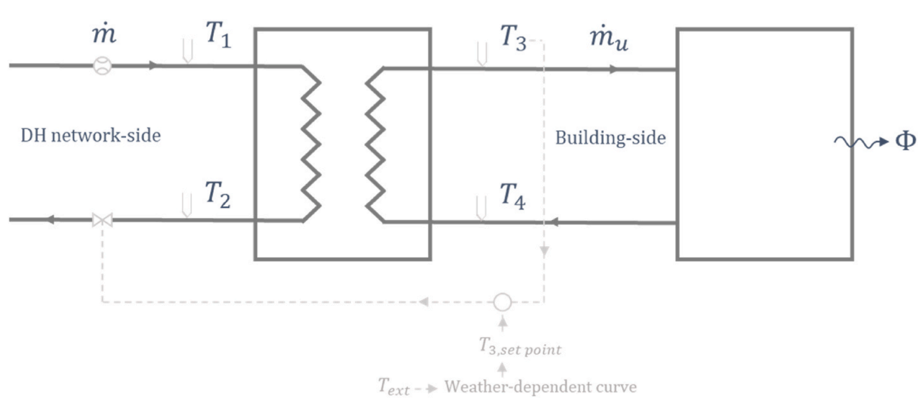

Fig. 2. Schematic of a thermal substation.

$$\varepsilon_{II} = \frac{1 - exp(-(1-\omega_{II})NTU_{II})}{1 - \omega_{II}\, exp(-(1-\omega_{II})NTU_{II})} \tag{6}$$

$$\omega_I = \frac{\min(\dot{m}, \dot{m}_u)}{\max(\dot{m}, \dot{m}_u)} \tag{7}$$

$$NTU_I = \frac{UA_I}{c_p \min(\dot{m}, \dot{m}_u)} \tag{8}$$

$$\omega_{II} = 0 \tag{9}$$

$$NTU_{II} = \frac{UA_{II}}{c_p\, \dot{m}_u} \tag{10}$$

The set of equations expressed by Eqs. 1–10 represents the substation model used in this work. This model can be adopted to reproduce the operation of the thermal substation when the supply temperature is decreased with respect to the current values. The model requires several input data: the mass-flow rate in the secondary circuit and the characteristics of the two heat exchangers. These two pieces of information are related to each specific substation and are usually unknown in real applications. In this study, the lack of data is addressed by processing data collected from the installed substations and elaborated by means of a proper automatic algorithm, which is developed in Section 2.2. Therefore, the mass-flow rate in the secondary circuit and the characteristics of the two heat exchangers (UA_I and UA_{II}) are obtained by using the substation data analysis. Φ and T_1 are input parameters of the model, since the heat flux required by the thermal substation should be guaranteed when the supply temperature is reduced. The corresponding mass flow rate to be supplied to the building is an output of the model and should be smaller than the maximum threshold, which is fixed to guarantee the applicability of the proposed solution. The problem expressed by Eqs. 1–10 turns out to be a nonlinear problem with 6 unknowns ($T_2, T_3, T_4, \dot{m}, \varepsilon_I, \varepsilon_{II}$) and 6 equations (Eqs. (1)–(6)). Solving the problem allows to obtain the required mass-flow needed on the primary side $\dot{m}$ along with the other operating temperatures of the thermal substation. This procedure is repeated for different values of supply temperature T_1, given a fixed value of the thermal power. This allows obtaining all the set of temperatures and mass flow rates that provide the same amount of thermal power Φ exchanged within the thermal substation. It should be noted that the energy equations alone do not guarantee the physical feasibility of the results: therefore, a check must be performed at the end of the calculation in order to verify that the solution satisfies all the temperature difference constraints. The entire procedure can be performed for different values of thermal demands (representative of different outdoor conditions). This allows to obtain a two-variables functions in the form $\dot{m}$ (T_1, Φ). The same applies to T_2 (T_1, Φ), while the supply temperature on the building side is a constraint and depends only on the thermal demand T_3 (Φ). These functions describe the physical behavior of each thermal substation. The operational limits are obtained by intersecting the 2D functions with the maximum mass flow rate that can be supplied to the thermal substation $\dot{m} = \dot{m}_{critical}$, thus obtaining a one-variable function T_1 (Φ). This represents the minimum set of supply temperatures that can be adopted for each value of heat flux (corresponding to different outdoor temperatures).

2.2. Data analysis

In this section, the methodology developed to estimate some useful parameters and variables of the heat exchangers using the measured substation data is discussed. This analysis is needed for estimating:

1. The characteristics of the heat exchangers of the existing substations (Subsection 2.2.2);
2. The mass-flow rate on the secondary circuit (Subsection 2.2.2);
3. The critical mass-flow rate, i.e. the maximum mass-flow rate processable by the thermal substation (Subsection 2.2.3);
4. The target thermal power at which the corresponding minimum supply temperature is estimated (Subsection 2.2.3).

The estimation of these quantities is preceded by a data pre-processing phase described in Subsection 2.2.1. The data analyzed are those typically collected by the substation measurement system (examples for the case study treated in this work are shown in Section 3):

- mass-flowrate circulating in the primary circuit $\dot{m}$;
- temperature at the inlet section of the primary circuit T_1;
- temperature at the outlet section of the primary circuit T_2;
- temperature at the inlet section of the secondary circuit T_3;
- temperature at the outlet section of the secondary circuit T_4.

2.2.1. Pre-processing and steady-state estimation

The first step of the data analysis is the *pre-processing/data correction*. This allows adjusting disturbed or unrealistic data (e.g. temperatures less than zero, temperatures greater than the network supply temperature, inconsistent temperatures like $T_1 < T_2$, $T_1 < T_3$, $T_1 < T_4$, $T_2 < T_4$, $T_3 < T_4$, outliers values in temperatures and/or mass-flow rates).

Then, an algorithm is developed to identify the *steady-state* operation of the substations. This step is essential because the operation of the substations can be very irregular (see the profiles described in Section 3), consisting of profiles with peaks requests and valleys (especially in Mediterranean regions, where the heating systems are attenuated or shut down during the nights, resulting in high thermal peaks when the heating is restarted in the morning). Steady-state conditions are needed to determine the characteristics of the heat exchanger required by the substation model, which is a steady-state model. For this purpose, the following actions are implemented in the algorithm:

1. A first check is performed on the differential of the thermal power $\Phi(t)$; if the increment of the thermal power exceeds a certain tolerance, the corresponding values are labelled as non-steady values; on the other hand, the values that are within the defined tolerance are subjected to further verification.
2. The remaining values are grouped into different intervals, each one containing only values that are consecutive over time. A minimum length of the time interval is established as a further criterion to identify steady-state operating conditions. All the intervals that do not meet the minimum length condition are considered as non-steady and excluded from the analysis.
3. A further verification consists in monitoring the variation of each measured quantity ($\dot{m}$, T_1, T_2, T_3 and T_4) within each interval. The values exceeding a predefined tolerance with respect to the corresponding interval average are removed.
4. Then, step (2) is repeated due to the variation in the steady values that occurred in step (3).
5. Finally, the values that are inside each steady interval are averaged in order to obtain a unique and more precise average operating condition for each steady-state ($\overline{\dot{m}}$, $\overline{T_1}$, $\overline{T_2}$, $\overline{T_3}$ and $\overline{T_4}$).

By implementing the proposed algorithm, it is possible to identify a larger or smaller set of steady-state operating conditions depending on the data availability and quality.

2.2.2. Evaluation of the technical performances of the heat exchangers

The steady-state conditions evaluated with the algorithm described in Section 2.2 are used to estimate the characteristics of the substations, namely secondary-side mass-flow rate and U A (the product of the heat transfer coefficient and the heat exchanger area) of the heat exchangers, which are needed to run the substation model discussed in Section 2.1.

The procedure adopted to estimate these characteristics is discussed in the following lines.

First of all, the mass flow rate circulating in the building circuit is computed using a steady-state balance derived from Eq. (1) and Eq. (2) and expressed by Eq. (11):

$$\overline{\dot{m}_u} = \frac{\overline{\dot{m}}(\overline{T_1} - \overline{T_2})}{\overline{T_3} - \overline{T_4}} \tag{11}$$

In the case the circulating pump on the secondary side is characterized by fixed rotational speed, this mass flow rate varies according to the fluid dynamic resistances of the heating circuit, which depend on the adjustments on the thermostatic valves. In the case the rotational speed is variable, there is an additional degree of freedom which can be used to optimize the operation. In the present application, the mass-flow rate on the secondary side is constant, since no significant variations can be observed on the results obtained from the monitored data at steady-state.

The product of heat transfer coefficient (U) and heat exchanger area (A) of the two heat exchangers is estimated using the Log Mean Temperature Difference method [45], according to Eq. (12):

$$UA = \frac{\overline{\Phi}}{LMTD} \tag{12}$$

The heat exchangers are assumed to be counterflow. By using the relation expressed by Eq. (12), multiple values of UA are found for the two heat exchangers (one value for each steady-state condition). In this study, for the first heat exchanger (HX1) the UA values are approximated using a linear regression, since they depend on the primary-side mass-flow rate, according to Eq. (13)

$$UA_I = UA_I(\overline{\dot{m}}) = a\overline{\dot{m}} + b \tag{13}$$

where a and b are constant coefficients. The other dependencies (e.g. the dependency on the secondary-side mass-flow rate) are neglected, since they have a minor contribution. Each linear function is then used to characterize the different substation heat exchangers (HX1). The dependency on $\dot{m}$ adds a further nonlinearity in the model.

On the other hand, for the fictitious heat exchanger (HX2), a constant average value – Eq (14) – can be used since the secondary side mass-flow rate is constant:

$$UA_{II} = k \tag{14}$$

The goodness of the assumptions will be proved in the validation given in the results section (Section 4). Nevertheless, the model proposed in this work can be easily adapted also to different kind of approximations (e.g. variable secondary-side mass-flow rate, non-linear behavior of UA) when these assumptions are considered not suitable for certain applications.

2.2.3. *Evaluation of the operating conditions for the calculation of the minimum supply temperature*

In order to obtain the minimum supply temperature at which each substation can operate given its steady-state thermal request, two additional pieces of information are needed for each substation.

1. The target thermal power value. This is the thermal demand of the building, in the conditions considered for the minimization of the supply temperature. In this paper, the analysis is performed considering all historical values available in the range of outdoor temperatures between 4 and 6 °C, which represents a very critical winter condition for the examined system: a lower temperature is registered in less than 5% of the time during the heating season. This means that the supply temperature estimated in the analysis is valid for more than 95% of the heating season. On colder days, a higher supply temperature is necessary, while in milder conditions even lower supply temperatures could be adopted. It is worth underlining that the data used for the analysis refer to the steady-state operation (typically recorded in daily hours), which means that these outdoor temperatures are representative of days in which the minimum temperature of the entire day may be significantly lower.
2. The critical mass-flow rate. This is the maximum mass-flow rate that each substation can process. This is due to the maximum pressure losses and the maximum velocity that the water can reach in the substations. Its value is determined by examining the available historical data for each substation, without considering the highest 100 values in order to exclude the outliers that might be related to wrong measurements and selecting the average of the next 1000 largest values. This is a conservative assumption since the highest mass-flow rate value historically recorded by the substation is necessarily lower than the actual acceptable mass-flow rate. Therefore, if the actual mass-flow rate constraint is higher than the identified critical value, even lower supply temperatures can be achieved with respect to the minimum supply temperature computed using this approach (thus representing an upper limit). The advantage of such an approach is also related to the fact that a smaller value in the critical mass flow rate increases the probability to obtain acceptable fluid flow conditions for the entire network, as discussed in Section 4.

Once these two values are obtained, they can be integrated with the results obtained from the substation model (as shown in Fig. 1) in order to extract the corresponding minimum supply temperature.

2.3. *Identification of minimum supply temperature*

The last step of the analysis consists in the identification of the minimum supply temperature for each thermal substation during the typical cold winter condition. Considering the whole network, the maximum value among the minimum temperatures of all the buildings should be considered as the minimum sustainable value for the case study considered. Moreover, the analysis of the distributions of the minimum temperatures can be used to plan specific interventions on the buildings or their substations, as discussed in the Results section.

A schematic representation of this process is given in Fig. 3. For each

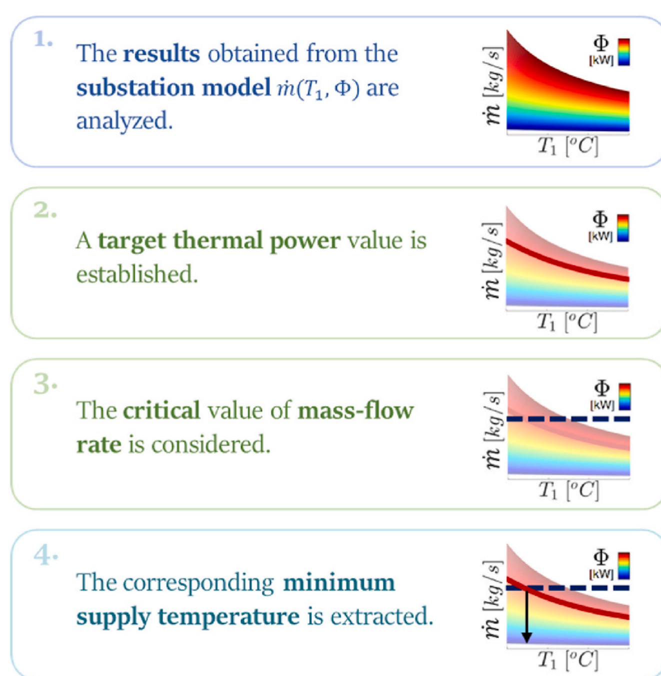

Fig. 3. Schematic representation of the procedure adopted to identify the minimum supply temperature of each substation.

thermal substation, a 2D function G (T_1, Φ) is estimated as described in Section 2.1; this graph provides an evaluation of the mass-flow rate $\dot{m}$ which is needed to supply a certain thermal power Φ as a function of the supply temperature T_1. In other terms, this represents a map of the physical behavior of the thermal substation for different operating conditions. The supply temperature is evaluated by cross-referencing this map with the quantities extracted from the data analysis, namely the critical mass flow rate and the target thermal power (Section 2.2.3). In this way, it is possible to obtain the minimum supply temperature, i.e. the minimum temperature that allows to provide the required thermal power without exceeding the mass-flow rate constraint. The results are presented in Section 4.

3. Case-study

Some case studies are introduced to show how the proposed methodology can be used to verify the potential for supply temperature reduction of real substations belonging to existing DH networks. In this study, reference is made to an existing DH network of a city located in Northern Italy. Nevertheless, the same methodology could be applied to different case studies, even located in northern countries with more critical temperatures and thermal demands, provided that sufficient data are available for the analysis.

Five distribution networks (also called sub-networks) connected to the main network and located in different areas of the city are analyzed. The total number of substations connected to each distribution network is reported in Fig. 4(a), along with the number of substations with available and reliable data (that are those analyzed in this study), and the total volume of the buildings connected. In total, 267 different substations are studied in this work.

The current supply temperature provided by the plants of the analyzed district heating network is currently around 120 °C. In Fig. 4 (b), the average substation supply temperature (T_1) of each sub-network is reported: this value is obtained as the average of the supply temperatures of all the substations connected to the specific sub-network. Alongside the average substation supply temperature (T_1), the average building supply temperature (T_3) is specified: this is the average of the set point temperatures of all the building's heating circuits connected to the specific sub-network. Both values are reported for particularly cold outdoor temperatures, considering the steady-state conditions occurring within the range of outdoor temperatures 4–6 °C; this is the temperature range considered as reference for cold days, since less than the ~5% of the steady-state conditions found are below this range. Observing the graph, it can be seen that in the case studies analyzed there could be a wide room for improvements in terms of supply temperature reduction at substation level: the current supply temperature of the substations is around 116 °C, while the temperature required by the building circuit is around 60 °C.

The substation measurement system provides a large amount of data: in the network analyzed, the four temperatures and the primary-circuit mass-flow rate are recorded every 5 min. For the five sub-networks considered, the measurements collected over 8 years (2012–2020) were available. It is worth mentioning that only the space-heating season (October 15th to April 15th in Northern Italy) is considered in this work since the supply of domestic hot water has a reduced share in this system.

In order to show the kind and trend of the data collected by the measurement system, some examples are reported in Fig. 5: in these graphs, the data collected during a winter day, representing the mass-flow rates, thermal loads, and supply/return temperatures on both the sides of the substation heat exchanger, are reported for one sample substation per sub-network. The peaks in mass-flow rate and thermal power are clearly evident in the corresponding graph; these are due to the attenuation/shut-down of the heating devices that is widespread in the area considered during the night and, in some cases, also during the day. For the sake of completeness, some specifications of the sample substations are given in in Table 1: the total volume of the building, which gives an idea of the dimensions of the specific case in the system analyzed, and the current average supply temperature (referring to the critical outdoor conditions specified above), which is useful to estimate the impact of the expected reduction. The sample substations all belong to private apartment buildings with different range of total volumes, ranging from 2000 m3 to 13200 m3 (corresponding to about 4–50 apartments per building), and connected to DH only for space-heating purposes. The same samples are also used in Section 4 to show some of the results obtained at substation level.

4. Results and discussion

In this section, the results of the study are reported and discussed.

4.1. Data preprocessing and data analysis

Firstly, the results of the preprocessing and data analysis are introduced. These and other intermediate results are shown for one sample substation for each subnetwork, as specified in Section 3 (Table 1).

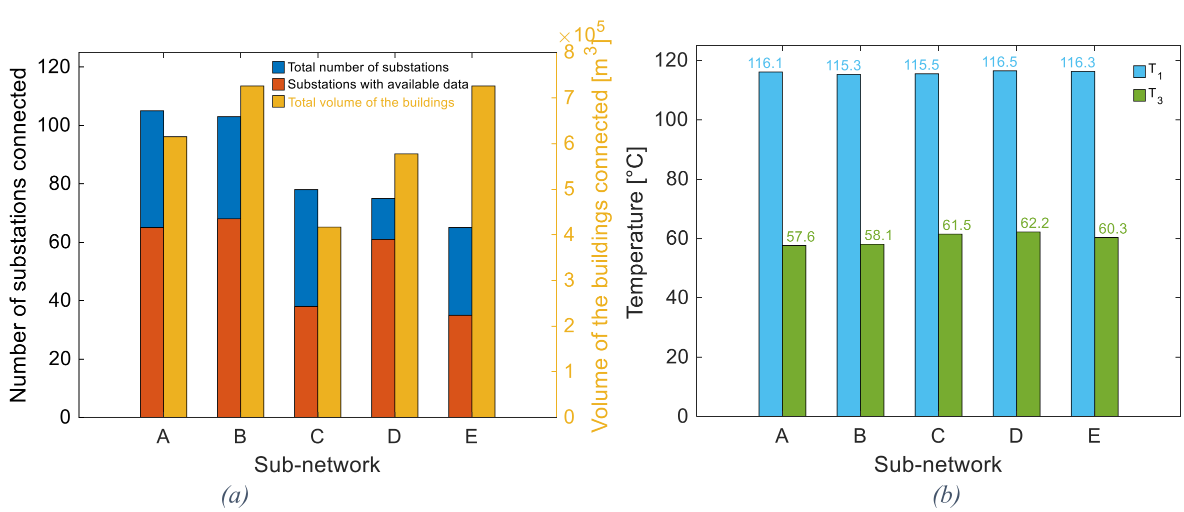

Fig. 4. Main characteristics of the five sub-networks: (a) On the left y-axis, total number of substations connected to each sub-network, and number of substations with available/reliable data; on the right y-axis, total volume of the buildings connected to each sub-network. (b) Average supply temperature of the substations (T1) and of the building heating circuit (T3) recorded at cold outdoor temperatures (4–6 °C).

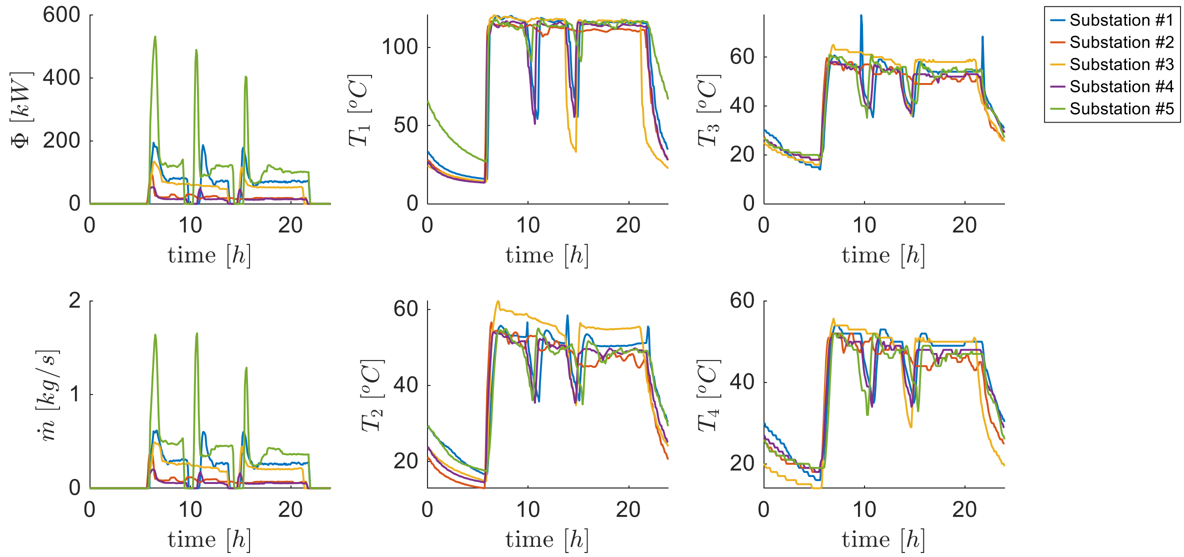

Fig. 5. Example of the data available for 5 different substations (belonging to the 5 different subnetworks analyzed) for a winter day. The data are collected every 5 min.

Table 1
Specifications of the sample substations of the different case studies.

Sample Substation	Sub-network	Volume of the building	Current average supply temperature
#1	A	6.3 dam^3	118.6 °C
#2	B	3.2 dam^3	114.3 °C
#3	C	4.1 dam^3	117.4 °C
#4	D	2.0 dam^3	116.8 °C
#5	E	13.2 dam^3	118.2 °C

In Fig. 6, the results of the steady-state identification algorithm are shown. As an example, the results for substation #5 are reported. This is the largest customer among those reported as samples. The substation is connected to a private apartment building serving several flats; as for the other cases, the specifications of the substation as well the performance of the heat exchanger are not known to the DH network company and are derived by means of the data analysis software. During the period reported in the figure, the substation is characterized by three different daily switch-ons. It can be seen that the algorithm properly identifies the three different sets of steady-state conditions by monitoring the variations of heat flux, mass-flowrate and temperatures as explained in Section 2.2. Similar results are obtained for the other substations.

In Figs. 7 and 8, the various average steady-state conditions that are identified for two substations (substation #2 from sub-network B and substation #3 from sub-network C) are reported as a function of the external temperature. A color bar is used to visualize possible variations in the behavior of the substation during the time period analyzed. It is possible to observe two different behaviors: Fig. 7 is representative of a thermal substation where the thermal request does not vary significantly

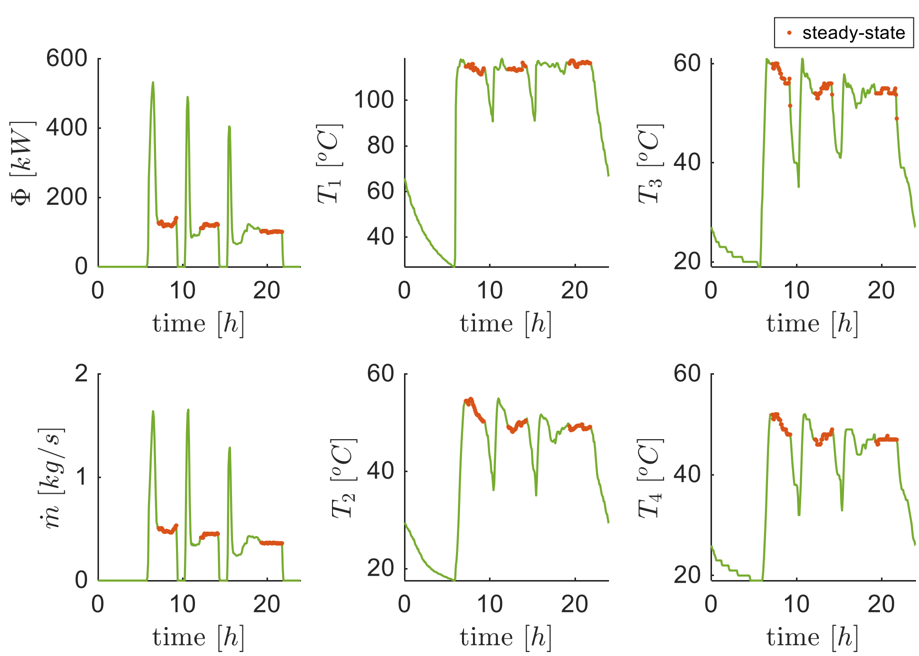

Fig. 6. Example of the output of the algorithm that identifies the steady-state operating conditions (Substation #5 from sub-network E, winter day): the continuous lines represent the evolution of the data collected by the measurement system; the red dots are the steady-state operating conditions identified by the algorithm.

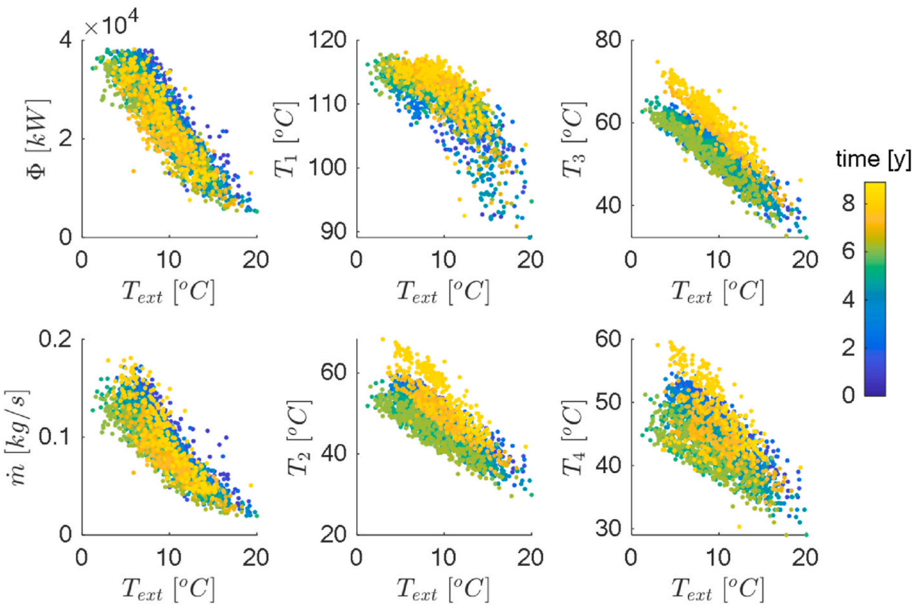

Fig. 7. Steady-state conditions for Substation #2 (Sub-network B) of thermal power, mass-flow rate and temperatures as a function of the external temperature.

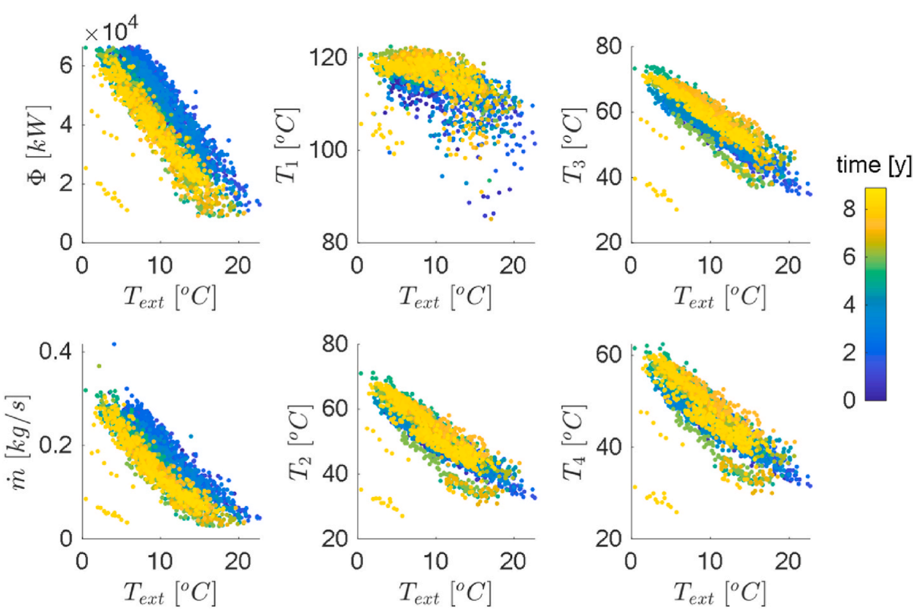

Fig. 8. Steady-state conditions for Substation #3 (sub-network C) of thermal power, mass-flow rate and temperatures as a function of the external temperature.

over the data period available (about 8 years); some variations are present in the temperature evolution, in particular in the temperature level required by the building (T_3), which increases over the years at the same outdoor temperature. By contrast, the substation reported in Fig. 8 shows a decrease in the thermal demand that could be attributed to renovations of the building or of the heating system; similar reductions in the thermal demand can be observed in many other substations. This is probably due to retrofitting work carried out during the period of the data considered. In these cases, the projected supply temperature is expected to be significantly lower than 120 °C, since the heat exchanger becomes more and more over-dimensioned with the reduction of the thermal demand.

The identified steady-state conditions are used to compute the *UA* coefficient, which is adopted to characterize the heat exchangers of each substation. In Fig. 9, the *UA* coefficient for the substation heat exchanger (*HX1*) is given as a function of the primary-side mass-flow rate for the five sample substations. The results obtained from the real data according to Eq. (11) show a clear linear dependency of this coefficient on the mass-flow rate, which can be attributed to the dependence of the heat transfer coefficient on the flow velocity. The corresponding linear interpolation used in the substation model is also shown in the figure. The final correlation $UA_I(\dot{m})$, along with UA_{II} of the fictitious heat exchanger and the secondary-side mass-flow rate (which are instead obtained as average values of all the days considering only the steady-state conditions, as discussed in Section 2.3), allows to get the full picture of the characteristics of the installed substations and, consequently, makes it possible to use the developed substation model.

4.2. Validation of the model

The substation model developed in this work is first used to perform a set of computations at constant mass-flow rate, in order to evaluate the

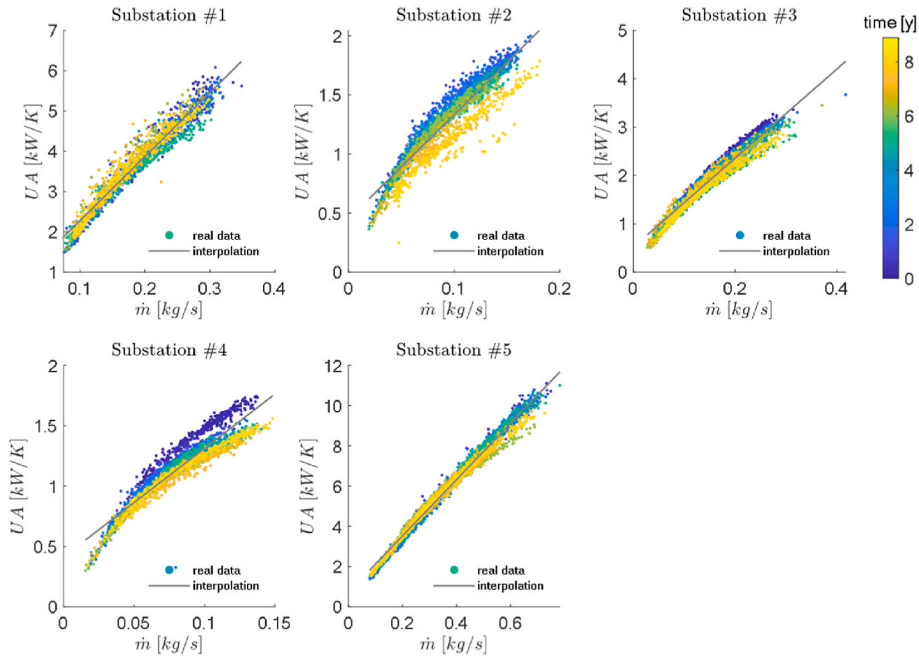

Fig. 9. Product of heat transfer coefficient (U) and heat exchanger area (A), calculated by substation data, of the first heat exchanger (HX1) as a function of the DH-side mass-flow rate.

decrease in the primary-side temperature difference and, consequently, the decrease in the thermal power provided to the substation when the supply temperature T_1 is lowered. In this case, the model discussed in Section 2.2 (Eq. (1) to (10)) are used considering $\dot{m}$ and T_1 as input of the model while Φ and T_2 are output. Considering substation #5, the results are shown in Fig. 10, where the model results are compared to the measured data. Measurements are only available at high supply temperatures, i.e. those currently adopted in the network. At first, the results give the opportunity to validate the proposed model. From the example shown in Fig. 10, it is possible to observe that the values computed by the model are in good agreement with the real measurements. To have a better estimation of the quality of the model, the relative error between the thermal power resulting from the model and the corresponding measurement is computed for each available steady-state value. Then, for each substation, an average relative error is calculated. In Fig. 11 a box plot of the relative errors is reported for each sub-network. The median value is around 5.7%. This can be considered an excellent result given the simplicity of the model, which is mandatory due to the few kind of data available for district heating analyses. Results are even more significant when observing that only few substations (about 5% of the sample) have errors higher than 10% (which could be due to insufficient data resolution or indoor conditions highly different from those hypothesized, i.e. $T_{indoor} = 20^{\circ}C$), while the majority of them shows relative errors within 2–5%.

4.3. Model results

Once the model is validated, the core results of the present research paper can be discussed. The substation model has been used to estimate the increase in the mass-flow rate that is needed, for different supply temperature values, to reach a target thermal power. This objective is achieved by using the substation model and considering as parameters Φ

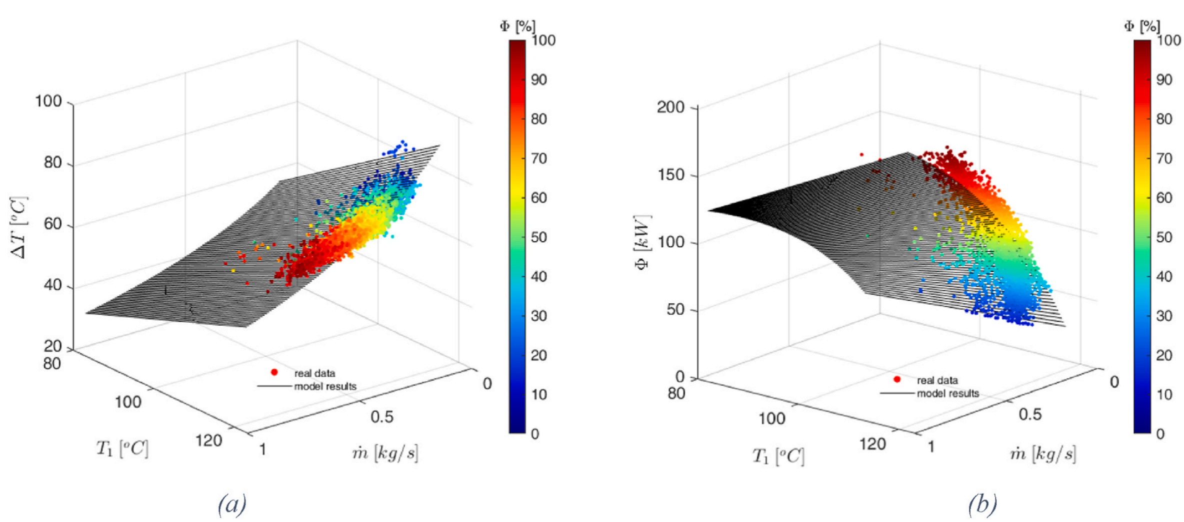

Fig. 10. Primary side temperature difference ($\Delta T = T_1 - T_2$) and thermal power provided to the substation (Φ) for different values of primary-side mass-flow rate $\dot{m}$ and supply temperature T_1 (substation #5, sub-network E).

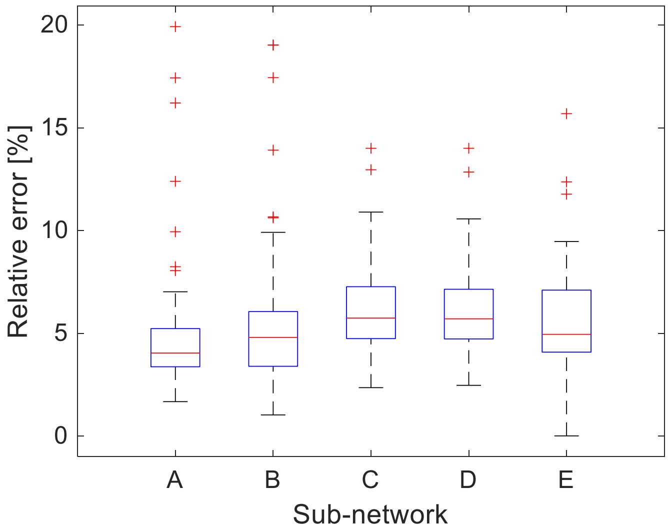

Fig. 11. Relative error between calculated and measured thermal flux for the different sub-networks analyzed.

(i.e. the target thermal power to be achieved) and T_1 (i.e. the temperature used to supply the substation), while $\dot{m}$ and T_2 are obtained as outputs. The results are shown in Fig. 12. As the supply temperature decreases, higher values of mass-flow rate are needed to obtain the thermal power required; this is related to the fact that the heat exchanger is no longer able to deliver the same heat as before with a lower supply temperature and the same mass-flow rate. The consequent increase in the mass-flow rate is observed to be more relevant for higher values of required thermal power. This means that at lower thermal demands, the expected increase in mass-flow rate due to the supply temperature reduction is lower. This is a positive aspect if considering the trend of energy consumption reduction in buildings, as well as performance improvement [46–48], also due to government incentives. This is a crucial aspect to enhance significant supply temperature reduction in existing DH substations.

The current minimum supply temperature of each substation has been evaluated using as target thermal power value the average of thermal power required by each substation during the last two years, when the outdoor temperature is in the range of 4–6 °C (as explained in Section 3, this can be considered as a critical cold temperature interval for the location considered). This guarantees that the value of supply temperature obtained can be applied for 95% of the heating season. Concerning the critical mass-flow rate, it is obtained using a dedicated algorithm, described in Section 2.1.3, whose results are reported in Fig. 13: it is possible to observe that the algorithm is conservative and capable of getting rid of outlier values.

The minimum supply temperature is evaluated for all the substations of the five distribution networks analyzed using the results of the previous analysis. Using the maximum value of mass-flow rate (critical mass-flow rate, shown in Fig. 11) and the target thermal power, the corresponding T_1 is extracted. This value represents the minimum supply temperature achievable by the considered substation; higher values of T_1 could be adopted because the corresponding mass-flow rate would be lower than the critical one, while lower values are not achievable because this would require exceeding the maximum mass-flow rate historically reached by the substation. The outcome of this analysis is illustrated in Fig. 14: for all the subnetworks analyzed, it would be possible to reduce the district heating supply temperature from around 116 °C up to 104 °C with the current configuration; this value is valid for the 95% of the heating season time. It is relevant to highlight that this potential reduction is associated with quite severe climate conditions for the considered district heating network (when systems located in northern countries are considered, a similar behavior is expected for lower outdoor temperatures). Even lower supply temperatures can be achieved for milder outdoor conditions because of the lower thermal loads; a possible way to exploit this further reduction would be the operation with a dynamic temperature approach, consisting in the dynamic variation of the DH supply temperature according to the corresponding outdoor air temperature [49].

Furthermore, if a target district heating supply temperature of 90 °C is imagined, just 27 out of 267 substations remain off target; being these substations a small percentage of the sample (10.1% in this case), local

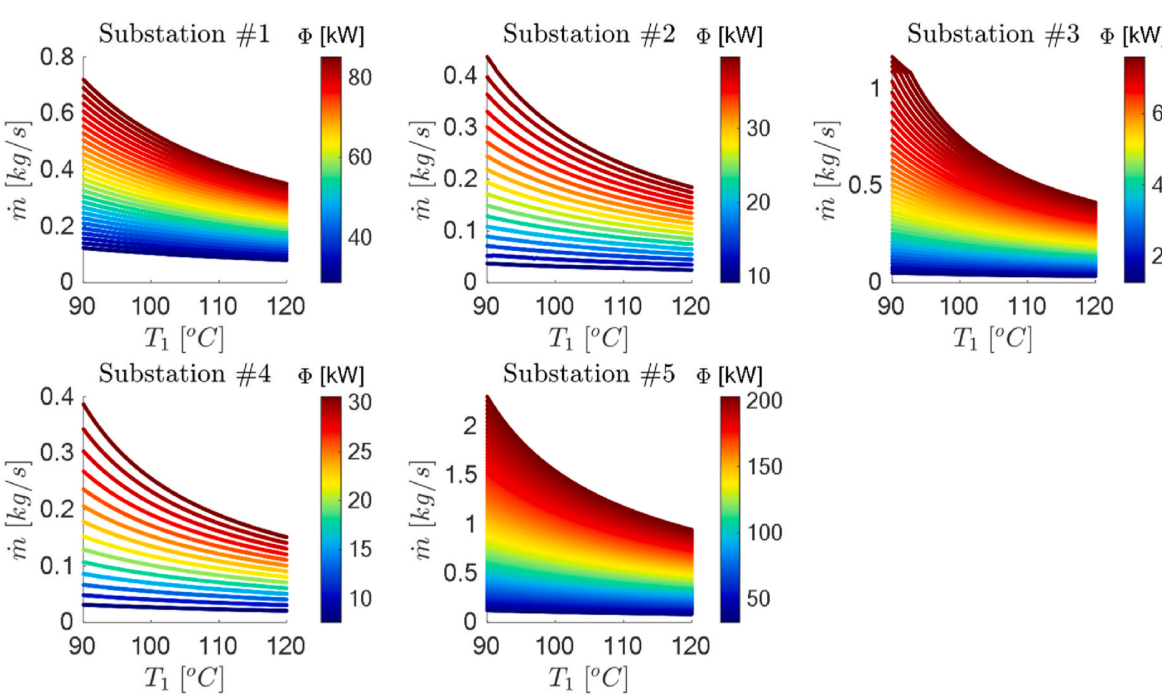

Fig. 12. Mass-flow rate ($\dot{m}$) required by the different sample substations to reach specific levels of thermal power Φ with different values of supply temperature T_1, obtained as results of the developed model (data analysis and substation model).

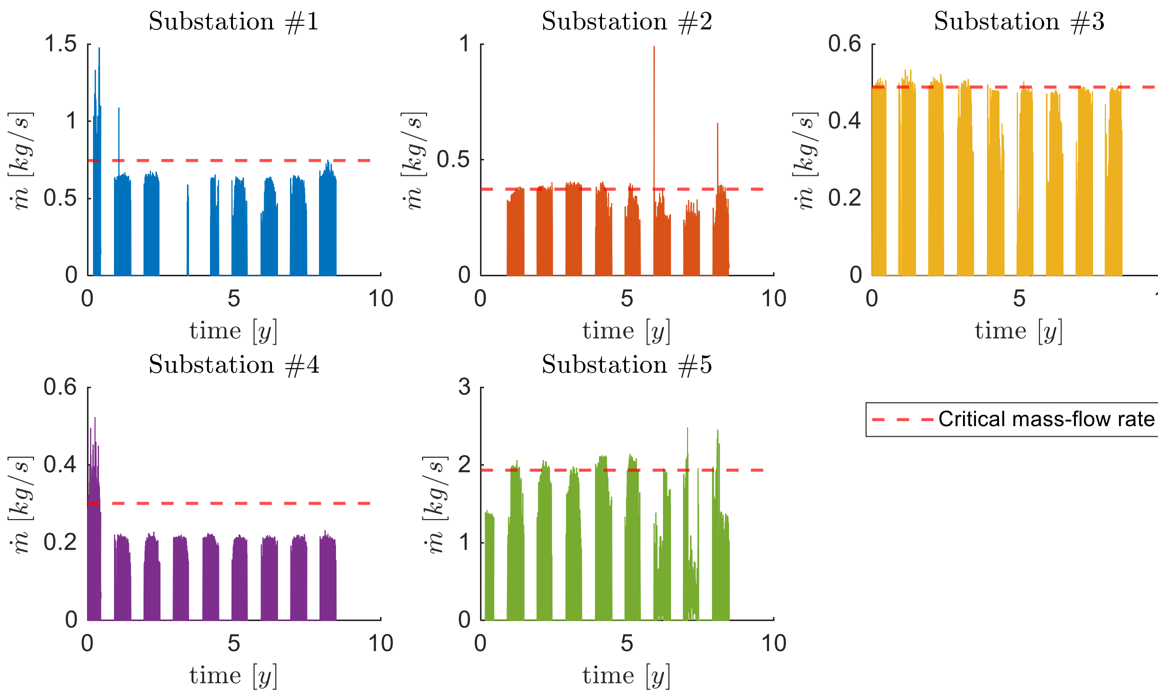

Fig. 13. Identification of the critical mass-flow rate for the five sample substations (continuous lines identify the whole set of transient data; the critical mass-flow rate identified by the algorithm is represented with a red dashed line).

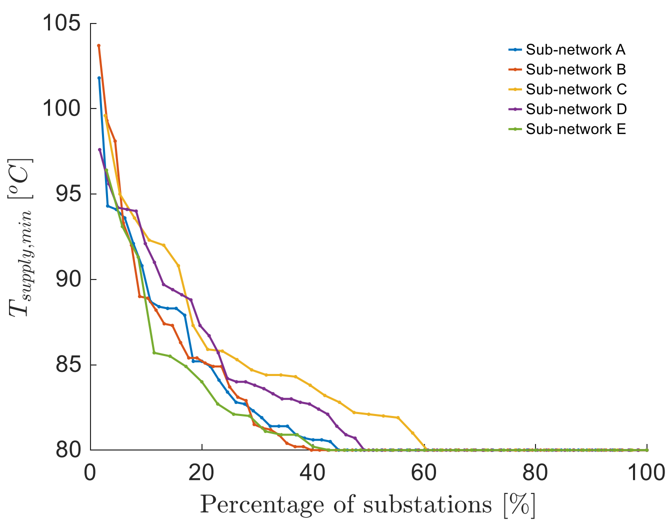

Fig. 14. Minimum supply temperatures achievable with low outdoor temperatures (4–6 °C) by the different substations of the five subnetworks analyzed.

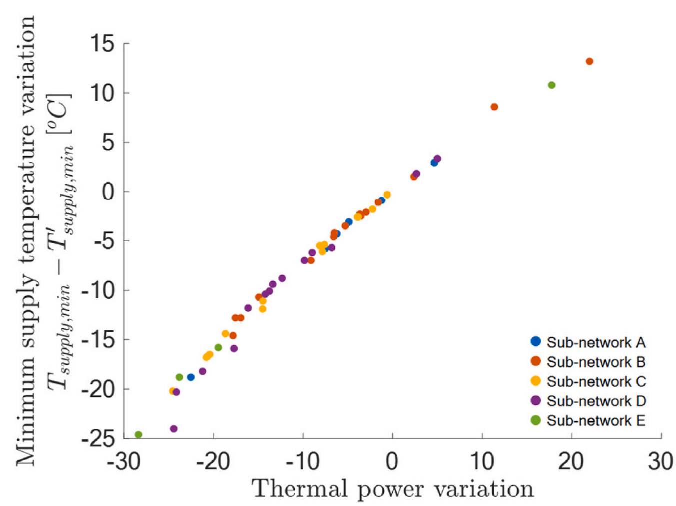

Fig. 15. Variation of the minimum supply temperature when the thermal power is modified.

interventions can be considered both at the building level or on at the substation level in order to enable the operation at lower supply temperatures.

Finally, in order to better analyze the dependency of the minimum supply temperature on the target thermal request, the procedure is repeated by varying the target thermal power of the substations. In detail, the target thermal power is re-evaluated considering older data (up to five years older than those previously mentioned). This analysis is performed just for the substations with sufficient number of data available in that period; most of them had a target thermal power higher than the current one. In Fig. 15, the variations of supply temperature are shown as a function of the relative thermal power variation. The behavior is almost linear, proving once again that great perspectives of supply temperature reduction in DH substations could be achieved in future scenarios with lower thermal requests in the buildings.

4.4. Results discussion and perspectives

The results of this analysis are encouraging with regard to the potential supply temperature reduction in district heating substations; application to a large-scale DH network in Northern Italy shows that all the installed substations currently fed at 116 °C can be supplied at 104 °C. The result does not represent a lower boundary, i.e. the best that can be achieved in existing substations. Rather, it can be considered as an upper boundary, i.e. the supply temperature that can be achieved without any modifications to the system. Indeed, there are several strategies that can be adopted at substation/building level to achieve further supply temperature reductions:

1) acting on the settings of the substations, after a proper analysis to identify the best operating conditions (e.g. set point temperature and thermal load profiles);
2) acting on the building's heating circuit (e.g. by varying the secondary-side mass flow rate);
3) replacing the heat exchanger of the substations that require the highest supply temperature;
4) retrofitting buildings, especially those that limit the minimum supply temperature;
5) adopting local heat pumps in large users that require heat at high temperature (e.g. hospitals);
6) automatically checking the possible presence of fouling in heat exchangers using a dedicated software [50,51], in order to keep the heat transfer coefficient as high as possible.

Furthermore, in this analysis the results were obtained with some conservative assumptions:

1) The maximum mass flow rate that the substation can process is estimated using the average of the maximum historical data. In reality, the substation may be able to operate at higher mass-flow rates. This could further reduce the supply temperature of the substations.
2) It does not take into account the effect of the retrofits that several buildings have carried out in the last two years thanks to the available incentives and those that are already planned.
3) A quite severe climatic condition is considered in the analysis; further reductions can be operated when the average outdoor temperature is larger. A dynamic temperature approach can be considered.

As concerns the applicability to other systems, despite the potential temperature reduction achieved was obtained for the specific case study, the developed methodology can be applied to a wide range of different applications, even located in different countries with more severe climates. While changing the boundary conditions, the final goal would remain to identify even in different cases the potential supply temperature reduction achievable, which would not actually depend on the boundary conditions themselves, but rather on the actual oversizing of the thermal substations compared to the current operation. In case of climates in which the thermal load significantly varies during the months, the dynamic temperature approach would assume an even higher relevance. Results are expected to be of the same order for the other networks for two main reasons:

1) The substations, independently of their location, are dimensioned for the coldest weather condition. This condition occurs very rarely. Therefore, in almost all actual operating conditions the substations result to be significantly over-dimensioned.
2) Often, especially in the case of large networks, the policies for the retrofitting action plan have been initiated after (or at least during) the network construction. In all these cases the over-dimensioning becomes even greater.

For all these reasons, it is expected that, in the future, the networks currently supplied with overheated water could be operated with hot water below 100 °C. Especially in the case of large networks, a specific analysis should be done on the suitability of the network infrastructure to carry the heat in the various areas of the urban center; this cannot be assessed without an advanced investigation with proper fluid-dynamic tools for the analysis of the pumping regulation, which is crucial to assure a complete exploitation of the network.

4.5. Preliminary analysis of the network

By analyzing the results discussed in the previous sections, it is evident that the existing DH substations have a great potential in terms of exploitable supply temperature reduction. In order to implement these changes in an existing network, the network itself must be able to support the increase in the mass-flow rates: besides heating devices and thermal substations, also the network components must be suitable for supply temperature reduction (e.g. the diameters of the pipes must be sufficiently large, the capacity of the circulating pumps must be suitable, …). To analyze in detail the network limitations, a full modelling of the thermo-fluid dynamic of the network is needed in order to carefully take into account all the specific limitations (e.g. concerning pressures and velocity constraints). This is beyond the specific scope of this paper, which is instead focused on the development of a methodology to assess the current limitations of existing substations, and it is left for discussion in future works specifically focused on network simulation using available network simulation tools [52,53].

Nevertheless, some preliminary considerations on the network can be drawn by adopting some assumptions:

- In order to verify whether the network is able to support the increase in the mass-flow rate, a faster and simpler first-approximation analysis based on measurements can be performed as an alternative to the full fluid-dynamic simulation. Fig. 14 shows that, once a temperature is selected (104 °C in the examined case), only a small number of substations are requested to operate with the limiting mass-flow rates or close values, while the majority of substations can operate with much lower mass flow rates; this is highlighted by the fact that they could theoretically operate with much smaller supply temperatures. Using these results, the total mass-flow rate which should circulate in the network can be calculated. This value can be compared with the sum of the mass-flow rates simultaneously requested by all the buildings connected to the DH network; in particular, the maximum value of this sum recorded in the historical data can be considered as a reference. Since the total required mass-flow rate is smaller than this value, it is highly probable that the temperature reduction is sustainable also for the network.
- An estimation of the exergy savings that can be achieved by reducing supply temperatures is provided in order to highlight the benefits that can be achieved by reducing the operational temperature independently of the energy source. This is obtained through a comparison of the exergy increase of the pumps associated to the mass-flow rate increase and the exergy savings achieved thanks to the temperature reduction. The calculation is performed considering a synthetic network with a thermal load of 300 MW_t with an electricity demand for pumping corresponding to about 0.5% of the heat delivery [1], i.e. 1.5 MW. The exergy flux increase of the pumps is equal to the pumping power increase, which is calculated as

$$\dot{E}_{pumps} = \frac{\dot{V}\Delta p_{pump}}{\eta_{pump}} \tag{15}$$

and can be estimated as proportional to the third power of the flow rate (since the pressure drop is proportional to the square of the flow rate). Instead, the exergy saving of the thermal plants is accounted for by using the definition

$$\dot{E} = \dot{m}c_p\left(T_{in} - T_{out} - T_0 \ln\frac{T_{in}}{T_{out}}\right) \tag{16}$$

and adopting the average values obtained from the present analysis. In Fig. 16, these two values are reported for the two final configurations analyzed: in both the scenarios with supply temperature of 104 °C (which can realistically be achieved by the substations considered) and 90 °C (which would require some improvements to the substations, thus also further reducing the pumping energy), the exergy saved by introducing this modification with respect to the current operation at 16 °C is far greater than the exergy increase of the pumps. This result confirms the sustainability of reducing supply temperatures in DH applications in spite of the increase in the total

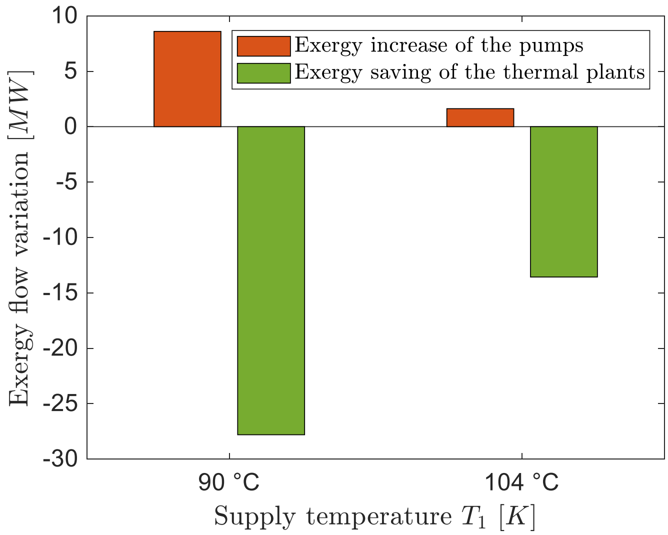

Fig. 16. Comparison of the exergy flow increase of the pumps and exergy savings of the heat production when supply temperatures are reduced with respect to the operation at 116 °C.

mass-flow rate. Additional advantages can be obtained considering that a lower supply temperature allows an easier integration of waste heat and renewable energy sources in the network. These advantages are strictly related to the available sources on the examined territory and, for this reason, are not specifically considered in the present analysis. Finally, further benefits are associated with the fact that, using lower supply temperatures, the pressurization of the network and of the various components including thermal energy storages can be significantly lowered.

5. Conclusions

Reducing operating temperatures in DH systems is among the most important goals to be reached in order to decarbonize this technology and to achieve a future sustainable energy system. This goal may be critical to be achieved in infrastructures that are already built and that were designed to operate with higher supply temperatures: important limitations can arise at the level of heating devices, thermal substations, and transport/distribution networks. The aim of this paper is to develop a valid approach to estimate the current potential for temperature reductions in existing DH substations. This means being able to estimate how much it is currently possible to reduce supply temperatures in thermal substations that were originally installed for operating at high temperatures.

To achieve this objective, a methodology is developed. This includes a physical model of the thermal substation and a data analysis software to estimate from experimental measurements (e.g. mass-flow rate and temperatures that are usually available to the DH operator for billing purposes) unknown data of the buildings/heat exchangers that are usually not known and that are needed to simulate the operation at low temperatures. Overall, the proposed model is able to reproduce with very good accuracy the operation of a thermal substation connected to a building, even when specific design data are not available, and to guarantee the thermal comfort conditions for users when supply temperatures are lowered.

The potential of the model lies in the fact that it can be applied to a wide set of existing DH substations to predict how much the supply temperature can be reduced without apporting any modification to the substation system. As an example, an application to a real DH network located in Northern Italy and involving a large sample of 267 different substations shows that using the thermal substations as they are currently installed, it is possible to reduce their supply temperature from 116 °C to at least 104 °C without affecting the comfort conditions. This result is very significant, especially if considering that it represents an upper boundary, since it is evaluated with the most critical outdoor conditions and since some conservative assumptions are included in the model. This means that even lower supply temperatures can be used during milder days, which becomes a significant advantage if a dynamic temperature approach (consisting in varying the supply temperature according to the climatic conditions) can be adopted. Moreover, supply temperatures can be further reduced by considering small modifications to the substation/building system. Firstly, it can be seen that the increase in the mass-flow rate due to the reduction of the supply temperature can be counterbalanced by the reduction of the thermal demand of the substations, since this effect is reduced at lower values of thermal power required; this represents a good opportunity in light of the current trend to improve the energy performance by decreasing the energy consumption of the buildings, which could contribute to further reduce the supply temperature of existing district heating substations. Other options include interventions in the substations, such as the implementation of a different control or, in the limiting cases, the substitution of the thermal substations that require the highest supply temperatures. For these reasons, it is highly probable that in the case study analyzed, in which only the 10% of the sample requires supply temperatures higher than 90 °C, this supply temperature value could realistically be achieved in the near future with few improvements to the substation/building system.

Having shown that existing substation systems can have great potential even without invasive interventions, it is necessary to verify that the distribution/transport network can also support the increase in mass-flow rate before the prospective supply temperature reduction can be implemented. While a preliminary analysis of the network proposed in this study shows that the potential could be quite good even for the network part, future work will be devoted to specifically analyze the fluid-dynamics of the network and to quantify its respective supply temperature reduction.

CRediT authorship contribution statement

Martina Capone: Conceptualization, Methodology, Software, Data curation, Writing – original draft, Visualization. **Elisa Guelpa:** Conceptualization, Methodology, Writing – review & editing, Visualization, Supervision. **Vittorio Verda:** Conceptualization, Methodology, Visualization, Supervision.

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.

Data availability

The authors do not have permission to share data.

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Nomenclature

c_p	Specific heat [J/kg/K]
$\dot{E}$	Exergy flow [W]
$LMTD$	Logarithmic mean temperature difference [K]
$\dot{m}$	Mass-flow rate, network side [kg/s]
$\dot{m}_u$	Mass-flow rate, building side [kg/s]
$\dot{m}_{tot}$	Plant total mass-flow rate [kg/s]
NTU	Number of transfer units [−]
p	Pressure [Pa]
t	Time [s]
T_{ext}	Outdoor temperature [K]
T_{in}	Supply temperature of the thermal plant [K]
T_{out}	Return temperature to the thermal plant [K]
T_0	Reference temperature [K]
T_1	Supply temperature, network side [K]
T_2	Return temperature, network side [K]
T_3	Supply temperature, building side [K]
T_4	Return temperature, building side [K]
U	Global heat transfer coefficient [W/(m2K)]
V	Volume of the building [m^3]
$\dot{V}$	Volume flow-rate [m^3/s]

Greek symbols

ε	Effectiveness [−]
η_{pump}	Total conversion efficiency for the circulation pump [−]
ω	Heat capacity ratio [−]
Φ	Thermal load [W]

Abbreviations and subscripts

I	Substation heat exchanger
II	Building equivalent heat exchanger

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