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Modelling of waste heat integration into an existing district heating network operating at different supply temperatures

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ABSTRACT

A promising way to make use of waste heat sources is to distribute the heat to nearby buildings via district heating systems to cover the heat demands of the buildings. The integration of a waste heat source into an existing district heating system must be studied in advance to avoid difficulties in network operation and to ensure the required heat supply to all connected buildings. Simultaneously, supply temperature reduction can improve the overall system efficiency and should also be considered for a sustainable transformation of existing district heating systems.
In this paper, we develop a district heating model with multiple supplying heat sources to study the influence of an additional integrated heat source and the effects of reduced supply temperatures on the network conditions. With the developed model, we investigate the waste heat integration into an existing district heating system at a German research facility campus. Therefore, we test different integrated waste heat shares to identify arising bottlenecks and to check for the sufficient heat supply to the connected consumers. Furthermore, we test the opportunity to additionally lowering the supply temperatures in the district heating network. The simulation results show that waste heat integration is possible at the investigated district heating system up to 40%. However, simultaneously lowering the supply temperature leads to greater challenges as more bottlenecks arise and additional buildings are affected by insufficient supply.

1. Introduction

In the building sector, where heat supply to buildings marks a significant energy consumption, district heating systems are a promising technology to utilise renewable and waste heat sources to decrease the climate impact of heat supply to buildings. District heating networks can utilise many different waste heat sources on various temperature levels to distribute heat to the connected buildings. Lund et al. define four different generations of district heating systems, which differ in temperature levels, type of working fluid or the ability of coupling to other energy systems, such as the gas or electricity grid [1]. First generation district heating systems distribute heat via steam, while the second generation provides heat with pressurised water at high temperatures above 100 °C. While an exclusively fossil-based heat supply characterises the first and second generation, the third generation of district heating also uses alternative heat sources such as industrial waste heat or biomass and is furthermore characterised by a medium-temperature level below 100 °C. Modern district heating systems of the fourth generation, which are mainly supplied by sustainable heat sources, are operated at low temperatures below 60 °C [1].

Heat supply by district heating is widespread in many countries, for example in Scandinavia and the Baltic region district heating is responsible for 50% of the heat supply to buildings [2]. However, most existing district heating systems are supplied by fossil-based heating plants; in Europe 35% of the combined heat and power (CHP) systems are fired by coal, 39% by gas, and only 11% by renewable energy sources [3]. To reduce carbon dioxide emissions in the building sector, the substitution of these heating plants by sustainable heat sources is essential. Therefore, the integration of waste heat or renewable heat sources in existing district heating systems is an essential step in the overall energy transition.

Jodeiri et al. provide an overview of several sustainable heat sources in district heating systems and describe the main challenges for their usage in district heating networks as well as the potential for converting district heating to modern systems of the fourth generation [4]. In [5], different categories of heat sources, such as industrial excess heat

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or waste water, are mapped in Denmark to highlight the usable heat potentials that can be used in district heating systems in combination with heat pumps. Furthermore, several studies focus on the potentials of specific waste heat sources and investigate the possibility of making these heat sources available in district heating networks, e.g. excess heat from supermarkets or power stations [6], from industrial processes [7], or from the cooling systems of data centres and high-performance computers [8–10].

Integrating additional heat sources into an existing district heating network is challenging, as the source temperature level often does not match the network temperatures or the geographical location is unfavourable for the network structure. In [11], the changed operating conditions in district heating networks due to the integration of decentralised heat sources are studied by simulation models. It is outlined that decentralised heat integration leads to reversed mass flows and thus to changing flow rates in the network, which results in fluctuating thermal stresses in the pipes. Kauko et al. test a prosumer integration in a district heating network using a dynamic network simulation [12]. They simulate different scenarios regarding the temperature level and the prosumer capacity and show that prosumer integration in combination with decreasing supply temperatures leads to lower heat losses, but also to increasing pump energy consumption. The challenging integration of an additional heat source into an existing district heating network is also investigated by Nord et al. [13]. They study the thermal and hydraulic effects in the district heating network at Trondheim University resulting from an additional integrated waste heat source. The simulation study shows that the additional heat integration can lead to pressure cones near the integration point, which affects the reliable supply of some connected consumers in the network.

In addition, the transition of existing district heating systems from high to medium or even to low temperatures is necessary to increase their distribution efficiency and to allow the integration of sustainable heat sources at low-temperature levels. Neirotti et al. investigate the possibilities of lowering the supply temperature in an existing system through simulations, considering the adaption of the district heating control and the partial renovation of the connected buildings [14]. A comprehensive review of limitations and possible measures of supply temperature reduction in existing district heating systems is presented by [15].

As seen in the studies mentioned above, district heating operation is often tested with simulation models. Such simulation models allow the investigation of the system behaviour and the identification of possible occurring problems before the system is adapted to the real world. Gross et al. develop a simulation framework to test a planned district heating network with different supply temperatures and additional prosumer integration [16]. In this framework, a hydraulic and a thermal network model are coupled by an iteration approach to describe the entire district heating behaviour. Other simulation tools using different simulation approaches are available in various programming languages, such as [17] and [18] design district heating models in Modelica, while [19] and [20] develop tools based on Python. Brown et al. give an overview of available modelling approaches with different objectives, such as modelling the different components in a district heating system or investigating the behaviour of the holistic distribution system [21]. Furthermore, they highlight several commercial tools and make an evaluation of these tools in a Pugh matrix.

The integration of a sustainable heat source into an existing district heating system is planned at the Forschungszentrum Jülich (FZJ), a research campus in North Rhine-Westphalia, Germany. Most of the approximately one hundred buildings on the campus are supplied by a local district heating system that is supplied by a gas-fired combined cooling, heat and power (CCHP) plant. However, a new heat source will be available as a high-performance computer (HPC) is being built on the FZJ campus, which will emit waste heat. This waste heat is to be integrated as an additional heat source into the local district heating system to reduce the heat supply from the gas-fired heating plant. The HPC is being built in an unfavourable position concerning the endeavour of waste heat integration as the installed district heating pipes in the vicinity of the HPC are located at the outskirts of the network and not designed for large mass flows. Hence, the mass flow conditions in the network will change due to the additional heat source, as shown in similar case studies by [11,13]. In addition to the waste heat integration, the system efficiency can be increased by lowering the supply temperatures in the network from high to medium temperatures. However, this would lead to increasing mass flows in the network. These changed operating conditions in the network can lead to bottlenecks or to insufficient heat supply of some connected buildings, which must be avoided. Thus, the additional waste heat integration needs to be studied before the real implementation.

Current district heating simulation studies to investigate the effects of waste heat integration or different supply temperatures often focus on newly constructed district heating systems but rarely on existing ones [22,23]. The simulation study by [14] investigates the influence of lowering district heating temperature on the connected consumers in existing networks but investigates a relatively small network with nine buildings. In general, dynamic district heating simulations to investigate different temperature levels [23] or additional waste heat integration [22] are carried out for relatively small district heating networks with less than thirty buildings.

District heating simulation studies for the combined investigation of waste heat integration and supply temperature reduction in large existing district heating systems are missing. In this study, we develop a district heating model to investigate the effects on a large existing district heating system caused by an additionally integrated waste heat source and supply temperature reduction. The basis of the simulation model used for this work is formed by a previous study, which is limited to the modelling of one heat source [24]. Hence, the model must be adapted to enable the simulation of multiple supplying heat sources.

After adapting the model, we investigate the waste heat integration at the FZJ campus and identify possible difficulties compared to the current status quo. Different simulations are carried out to test various waste heat shares and to analyse the impact of lower supply temperatures, evaluating the effects on the installed pipes and the supply to the buildings.

The paper is structured as follows: In Section 2, we give an overview of the simulation model and the general modelling approach considering multiple heat sources in a district heating system. In Section 3, we study the waste heat integration at the FZJ campus and show the resulting simulation model for this use case. Subsequently, in Section 4, the integration of an additional heat source in the model is evaluated and the results of the district heating operation of the FZJ campus are presented. After discussing the results in Section 5, we summarise the study in Section 6.

2. Methodology

To investigate operational changes in district heating networks due to an additional heat source integration, we use an existing simulation approach for district heating systems in Modelica [24] and extend the simulation model to simulate the operation with two heat sources. First, we present the simulation approach for large district heating networks in Modelica. Second, we describe the model extension. Third, we present how the changed district heating operation is evaluated.

2.1. District heating simulation model

The simulation model of district heating is modelled in Modelica and uses the open source Modelica library AixLib for the supply, demand, and pipe model [25]. The model uses the open-loop simulation approach that is characterised by the fact that the mass flow input and output of the supply and demand models are hydraulically decoupled, which reduces the model complexity. The open-loop approach is used

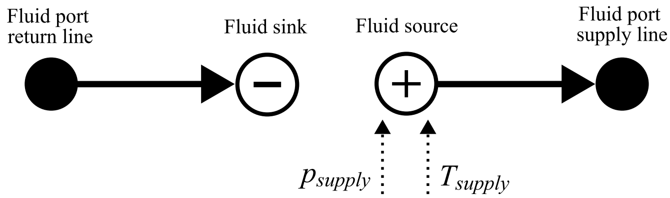

Fig. 1. Open-loop supply model with a fluid source and a fluid sink. The pressure p_{supply} and temperature T_{supply} conditions are set at the fluid source.

for large district heating system with a high amount of implemented consumer models to reduce computational complexity. The open-loop approach is suitable for this study, since the main focus is on the feasible heat distribution via the existing pipe network and not on the operational control of the connected substations or the supplying heat sources.

In the open-loop supply submodel *SourceIdeal* of the AixLib library, a mass flow at the fluid source is specified with a pressure p_{supply} and a temperature T_{supply} and is connected to the output port of the submodel, symbolising the supply line of the district heating network. The input port of the supply model, which symbolises the return line of the network, is connected to a fluid sink. The structure of the demand model is visualised in Fig. 1.

In the open-loop demand model *VarTSupplyDp* for the connected buildings, the required mass flow is calculated based on the heat demand, the design return temperature, and the incoming supply temperature. As with the supply model, also the input and output fluid ports are hydraulically decoupled in the demand model.

The pipe model of the district heating model is the *PlugFlowPipe* model of the AixLib model library developed in [26]. The plug-flow pipe model simulates the pressure and heat losses in a pipe segment and considers the temperature wave in the working fluid [26]. Thus, this pipe submodel enables a dynamic investigation of the district heating operation, as the heat propagation in the network is also taken into account. However, due to the complexity of the plug-flow pipe model, short pipe segments in the network are modelled with the *StaticPipe* model, which is also available in the AixLib library, in order to reduce computational costs [24].

In large district heating networks, long distances between forks consist of several small pipe segments due to bending paths or expansion loops. Representing all these pipe segments as pipe submodels in Modelica is computationally expensive. Therefore, the pipe topology of the network is simplified by aggregating several smaller pipe segments into one pipe segment to simplify the model and reduce the overall complexity [24]. Following the work of [24], this allocation step aggregates the friction loss factors due to bends or fittings in the network into a comprehensive factor representing the total friction loss of all aggregated pipe segments.

The entire district heating simulation model is automatically created by the Python framework uesgraphs, which exports run-able Modelica models based on the graphical representation of district heating networks [17]. Uesgraphs is an energy network tool that represents one or multiple energy network structures as graphs and handles the specific network information about supply, demand or distribution lines as attributes. Based on these attributes in the graph representation, Modelica submodels are parameterised with a Python template approach and connected to an holistic simulation model, e.g. a district heating network [17]. This approach of representing energy networks and the possibility of an automatic model export facilitate the creation of large district heating simulation models. In addition, minor adjustments to the attributes of the supply or the consumers in the graphical representation allow a quick adaption of the simulation model. This way, different simulation scenarios can be generated automatically, enabling the investigation of different district heating configurations, such as changing supply temperatures.

2.2. Extension of simulation approach by additional heat source supply

In order to investigate the district heating operation with an additional decentralised heat source, we use the described open-loop simulation approach for large network structures and extend the model to consider a second supplying heat source. Here, the supply ratio of the heat sources must be controllable. The additional heat source is integrated from the return line to the supply line of the network. Therefore, the set supply temperatures of both heat sources must be the same to avoid insufficient temperature supply in some areas of the network [27].

The previously described open-loop supply model *SourceIdeal* from AixLib is used for the heat sources. The ratio of supplied heat between the heat sources q_{heat} is described via

$$q_{\text{heat}} = \frac{\dot{Q}_{\text{add}}}{\dot{Q}_{\text{add}} + \dot{Q}_{\text{main}}}, \tag{1}$$

with $\dot{Q}_{\text{main}}$ for the heat supply of the main heat source and $\dot{Q}_{\text{add}}$ for the heat supply of the additional integrated heat source.

Since both heat sources have to supply heat at the same supply temperature, the mass flow ratio between the heat sources can be used to control the amount of supplied heat. By setting different supply pressures at the fluid sources (see Fig. 1), the pressure ratios in the network change and, thus, the resulting mass flows at the heat sources differ. The actually supplied heat at the heat sources can be calculated from the set supply temperature, the measured return temperature at the fluid sink, and the measured mass flow at a fluid port of the model. By measuring the supplied heat of both heat sources and comparing it with the specified heat ratio q_{heat}, the supply pressure ratio is adapted via a controller to change the mass flow ratio and, thus, control the heat supply. Fig. 2 visualises the described control approach.

In addition to controlling the mass flows in the supply line, the mass flows in the return line of the network must be regulated, since the fluid source and fluid sink in the models are hydraulically decoupled. Therefore, the supply model *SourceIdeal* of one heat source is adapted to control the mass flow ratios in the return line to maintain the same mass inflows and outflows at the heat sources. The adapted supply model compares the mass outflow to the inflow. Depending on the deviation between these mass flows, a controller adjusts the pressure condition at the fluid sink in such a way that incoming and outgoing flow at the supply model are equal. The supply model of the second heat source is not adapted and therefore the pressure condition at its fluid sink remains unaffected. However, by controlling the balanced mass flow at one heat source in the network, the resulting incoming and outgoing mass flows at the other heat source are also identical. The adapted supply model is schematically shown in Fig. 3 and applied to the additional heat source in the network model, while the main heat source is still modelled by the original supply model of the AixLib (Fig. 1).

Finally, we implement the described extensions to model and control a second heat source in the uesgraphs framework to automatically generate different parameterised district heating models to investigate various scenarios that are further defined in Section 3.3.

2.3. Changed district heating operation

In order to evaluate the feasibility of district heating operation, the used evaluation parameters are presented in the following.

2.3.1. Arising bottlenecks

The additional heat integration into the existing network structure leads to changed mass flow conditions in the pipes. Both the magnitude and the mass flow direction in the pipes change, as the amount of distributed heat increases in some part of the network. Changing mass flow conditions can lead to new bottlenecks in the network structure, especially due to higher mass flows in pipes that were not initially designed for such capacities. In addition, the mass flows increase by lowering the

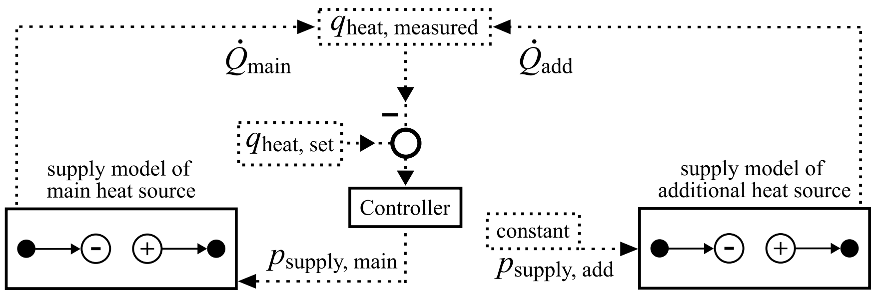

Fig. 2. Control approach of supplied heat: The actual heat supply from the heat sources is measured, and the heat ratio $q_{\text{heat,measured}}$ is calculated. The measured ratio is compared to the set heat ratio $q_{\text{heat,set}}$ and the deviation is used as an input to a controller that regulates the supply pressure at the main heat source, while the supply pressure at the additional heat source is set to a constant value.

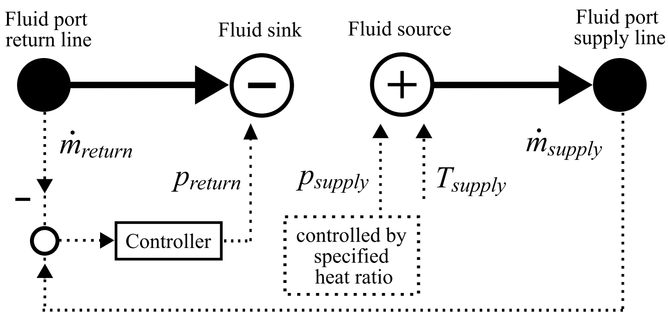

Fig. 3. Adapted supply model to control the pressure condition at the fluid sink to achieve balanced mass flow ratios between the return line and the supply line.

supply temperature in the district heating system while both the return temperature and heat demand are kept constant. Therefore, we evaluate the structure of the district heating network regarding occurring bottlenecks and check for critical pipe segments in which the occurring pressure loss exceed 250 Pa/m, following the suggestion of [28].

2.3.2. Supply temperatures at the consumers

Due to the changed mass flow conditions in the network, slow mass flow rates or even stagnant flow points can occur. Such mass flow conditions can lead to high heat losses to the environment and high temperature drops of the fluid and, thus, ultimately to insufficient supply temperatures at some buildings. Therefore, the heat supply conditions at each building must be investigated and evaluated to ensure that the incoming heat supply on the substation primary side, i.e. the network side, is sufficient for the building to operate its heating system on the secondary side of the substation. In this study, no adjustments on the consumer side are considered, and thus the current heat and temperature requirements of the connected buildings must be fulfilled.

To evaluate the sufficient heat supply, we calculate the temperature difference between the primary and secondary side of each substation. For each building, the required temperature level of the heating system, related to its heating curve, is calculated. Based on this required temperature on the secondary side and an assumed temperature difference of 3 K at the heat exchanger in the substation, the required supply temperature on the primary side is determined. This required supply temperature at the primary side is compared to the supply temperature resulting from the simulation results.

We calculate a key-performance index for the critical buildings with temporary insufficient supply temperatures to estimate the extent of insufficient temperature supply occurring. Therefore, we declare an index of insufficient supply temperature (IST) oriented to the DIN EN 15251 standard, in which the lack of comfort for rooms is calculated by weighting the violating temperature difference with the time duration [29]. For the critical buildings in the district heating network, we calculate the IST as follows

$$IST = \sum_{i=1}^{n=8760} \Delta T_{\text{HX},i} \cdot \Delta t_i \text{, where}$$

$$\Delta T_{\text{HX},i} = \begin{cases} 0, & \text{if } T_{\text{supply},i} \geq T_{\text{req},i} \\ T_{\text{req},i} - T_{\text{supply},i}, & \text{if } T_{\text{supply},i} < T_{\text{req},i} \end{cases}. \quad (2)$$

Thus, the summation of all time steps Δt_i (in h) is multiplied by the occurring temperature differences at the heat exchanger $\Delta T_{\text{HX},i}$ (in K) if the available supply temperature $T_{\text{supply},i}$ is below the required one $T_{\text{req},i}$ at this time step, otherwise it is multiplied by zero. The critical time steps are summed up over one year. Since the time steps Δt_i are summarised hourly, the unit of IST is K h. The summed up time duration with insufficient supply temperatures t_{IST} is also presented to indicate the relationship between time duration and occurring temperature difference at insufficient supply.

3. Case study

In this section, we describe the investigated use case at FZJ. After we present the resulting simulation model of the FZJ district heating system, the scenarios of the simulation study are listed with the considered boundary conditions.

3.1. District heating system and waste heat source

The FZJ is a research campus in Germany where different scientific disciplines are settled. Almost all buildings on the campus that are used as laboratories or offices are connected to the local district heating system for heat supply. The central CCHP plant, housing three gas-fired CHP units and two additional heat boilers for peak loads, covers the heat demand of all buildings, which is about 95 GWh/a. Currently, the network is operated at high supply temperatures of 95-132 °C controlled by a heating curve that depends on the ambient temperature. The design return temperature of the network is 65 °C. The current system design can be allocated to the second generation of district heating. The structure of the district heating network and the location of the CCHP plant are shown in Fig. 4.

A new HPC is being constructed on the FZJ campus, which will release a large amount of waste heat through its operation. The HPC is located in the north of the campus (see Fig. 4). The waste heat source is estimated to have a heat output of about 18 MW at a constant level, as the HPC is expected to run at a high load throughout the year. The FZJ plans to use the upcoming waste heat source in the local district heating network as an additional decentralised heat supply source. By integrating the waste heat into the district heating system, CO_2 emissions will be reduced as the supplied heat by the current gas-based heating plant will be partially substituted.

For the waste heat integration, the following restrictions must be considered. The waste heat cannot be integrated into the return line, as the return temperature should not exceed the current design temperature of 65 °C due to operational constraints of the CHP units. Therefore,

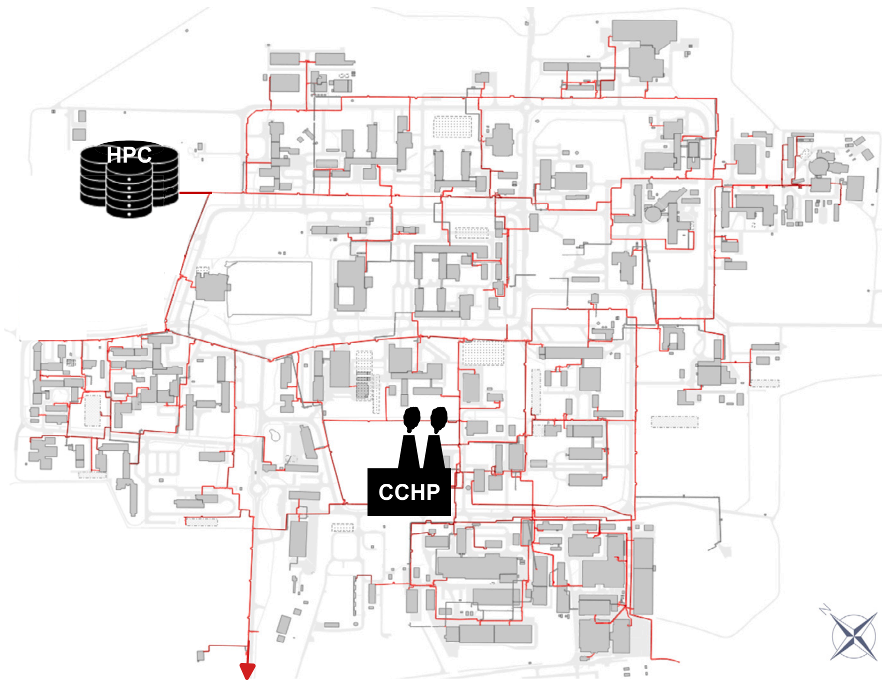

Fig. 4. District heating network structure at the FZJ campus. The location of the CCHP and the HPC are marked. At the bottom, a pipe to a more distant building is cut off (see arrow) for clarity.

the waste heat has to be integrated from the return to the supply line of the network and thus has to be at the same temperature level as the CCHP plant to avoid operational failures. As the waste heat of the HPC will be available at a low temperature level of approximately 44 °C, one or multiple heat pump systems are required to raise the waste heat temperature to the current supply temperature level determined by the CCHP plant. However, only the amount of integrated waste heat is considered, as the operation of the required heat pump system is outside of the scope of this study. For further studies on the environmental and ecological performance of waste heat integration in combination with a heat pump system and its influence on the current CCHP operation, we refer to [30].

As can be seen in Fig. 4, the HPC waste heat source is not located near the CCHP plant. The pipe capacities of the district heating network in the vicinity of the waste heat source were initially not designed to distribute a large amount of heat. Therefore, the decentralised integration of waste heat into the existing district heating network must be investigated in detail to ensure a feasible heat distribution.

3.2. Simulation of decentralised heat integration at FZJ

The original district heating network of the FZJ with one central heat source has been already created in uesgraphs and modelled in Modelica by [24]. However, the network structure has changed somewhat since the model was created, as nine buildings have been separated from the main network structure to set up a standalone low-temperature district heating system supplied by another HPC already in operation [31].

In this study, we take the model created by [24], remove the buildings that are no longer supplied by the main district heating system, and extend the simulation model as described in Section 2.2 to include an additional decentralised heat source. The resulting network simulation model with the main heat source, i.e. the CCHP plant, and the additional heat source, i.e. the waste heat integration, is visualised in Fig. 5.

Considering the pipe diameters in the vicinity of the waste heat source, a nearby integration point with a relatively large diameter is chosen for the waste heat integration. We simulate the district heating operation over one year with a time step of 3,600 s. The heat demands of the buildings are taken from measured data of the year 2017.

3.3. Studied simulation scenarios

For the FZJ case study, the effects of decentralised heat integration into the existing network topology are investigated with regard to the pipe network and the connected buildings. To evaluate the impact of different amounts of waste heat integration and reduced supply temperatures in the network, we use uesgraphs to export several district heating simulation models with various boundary conditions.

First, we vary the amount of integrated waste heat. Different levels of heat supply by the waste heat source lead to different mass flow conditions in the network and thus possibly to changed critical areas in the network. Therefore, we investigate different shares (20%, 30% and 40%) of waste heat supply based on the total required supply, so-called waste heat shares. The described control strategy, which specifies the heat ratio between the two heat sources q_{heat}, is adapted to these waste heat shares.

Furthermore, we also study the effects of reducing the supply temperatures of the network as part of district heating transition towards a newer generation. Reduced supply temperatures lead to lower heat losses and, furthermore, to a more efficient heat pump operation, as the temperature difference between heat source and supply temperature is reduced. In addition to the current high temperatures (HT) of 95-132 °C, we simulate the district heating system with medium supply temperatures (MT) of 80-100 °C that can be allocated to the third generation of district heating. Both heating curves are shown in Fig. 6.

The current temperature requirements of the heating systems of the buildings must be met. The heating systems of the supplied buildings are designed for 70/55 °C during the coldest days. Therefore, the design return temperature of the district heating system could not be reduced as much as the supply temperatures. Considering the temperature loss at the heat exchanger, the design return temperature is set to 60 °C for the scenarios with medium supply temperatures.

An additional simulation scenario is carried out for the reference operation (Ref_0) of the district heating system with only the main heat source in order to evaluate the effects of waste heat integration to the

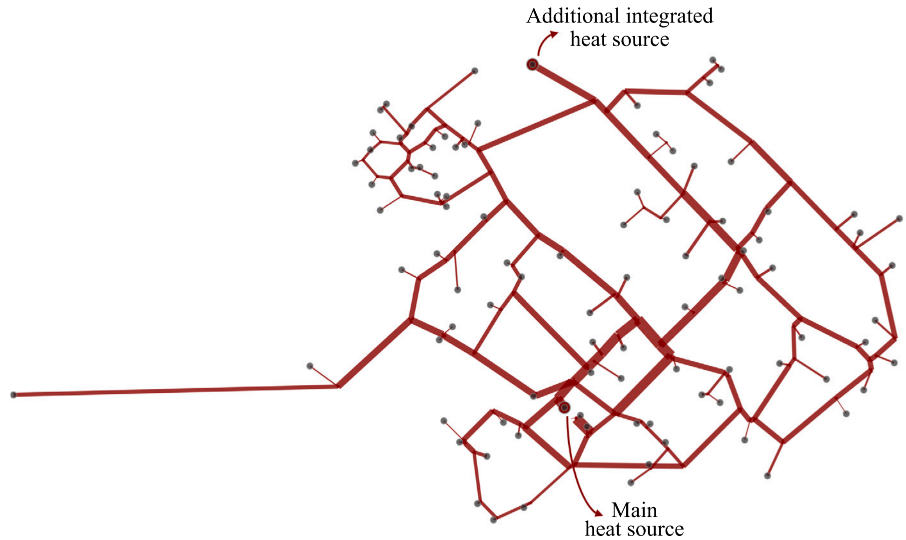

Fig. 5. District heating simulation model of the FZJ network with two heat sources: The model is visualised in uesgraphs with aggregated pipe segments. The nodes of the heat sources are labelled. The connected buildings are marked with grey nodes and the edge thickness represents the diameters of the network pipes. Note that the visualised model is north-orientated and not rotated as the network visualisation in Fig. 4.

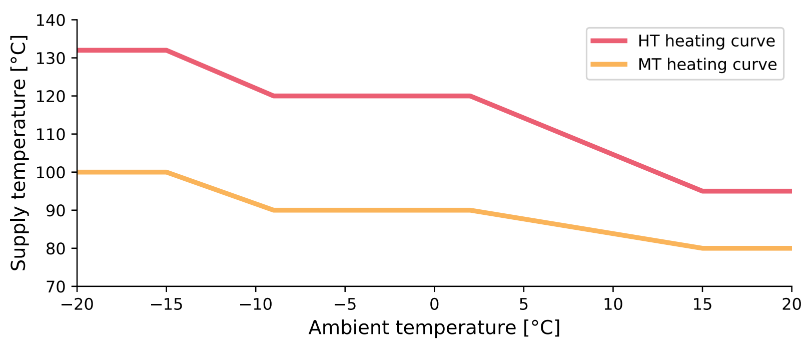

Fig. 6. HT and reduced MT heating curve for supply temperatures of the FZJ district heating system.

Table 1
Simulation scenarios for additional waste heat integration at the FZJ district heating system.

Scenario	Waste heat share in the district heating system [%]	Supply temperatures at heat sources [°C]
Ref_0	0	132-95
HT_{20}	20	132-95
HT_{30}	30	132-95
HT_{40}	40	132-95
MT_{20}	20	100-80
MT_{30}	30	100-80
MT_{40}	40	100-80

status quo. Table 1 summarises all simulation scenarios examined to investigate the effects of waste heat integration into the FZJ district heating system.

4. Results

In the following, we first verify the extended simulation approach. Second, we show the results of the reference district heating simulation with one heat source. Third, we evaluate the results of additional waste heat integration into the district heating system.

4.1. Evaluation of the extended simulation approach

In Fig. 7, the mass flows of the main and the additional heat source are presented exemplary for scenario HT_{30}. Comparing the mass flows in the supply line in the upper graph and the corresponding mass flows in the return line in the lower graph, it can be seen that the incoming and outgoing mass flows for each heat source are balanced. The mean mass flow difference at the controlled supply model, in this case the additional heat source, is at 1.6e-5 kg/s for scenario HT_{30}. At the main heat source, the return pressure remains unchanged, but due to the control of the additional heat source, the mass flow difference between outgoing and incoming mass flow at this heat source is balanced within the same tolerance.

The supply temperature and the pressure level at the supply line of both heat sources for scenario HT_{30} are shown in Fig. 8. Since the set supply temperature is the same for both heat sources, only one temperature plot can be seen in the upper graph of Fig. 8. However, focusing on the pressure at the supply line in the lower graph, it can be seen that the pressure at the additional heat source is fixed at 12.8 bar and the pressure at the main heat source is controlled to achieve the required mass flow ratio and, thus, the prescribed heat ratio (see also Fig. 2).

Fig. 9 shows the heat supply at both heat sources and the resulting heat ratio, i.e. the waste heat share, for scenario HT_{30}. It can be seen that the main heat source supplies more heat to the district heating system than the additional heat sources. The actual heat ratio between the main and additional heat source shows that the specified heat ratio of 30% is met with only minor deviations.

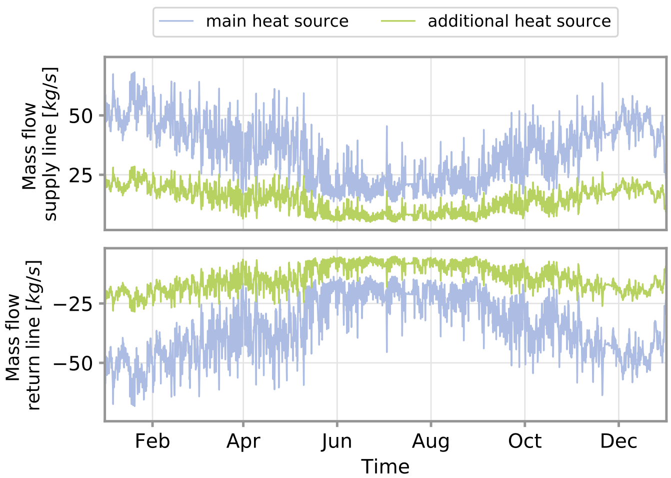

Fig. 7. Mass flows at the supply line and the return line of the two heat sources for scenario HT_{30}.

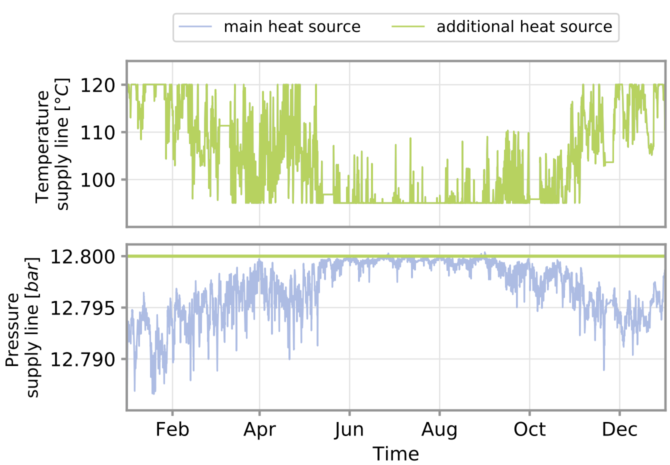

Fig. 8. Supply temperature and pressure of main and additional heat source of scenario HT_{30}.

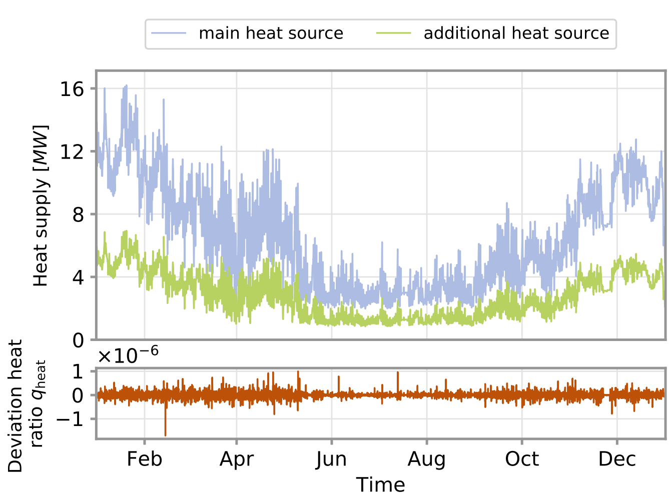

Fig. 9. Heat supply of main and additional heat source and the deviation from the set heat ratio of scenario HT_{30}.

Table 2
IST of critical buildings and time duration of insufficient supply t_{IST} for the reference district heating simulation.

	Ref_0	
Building	IST [K h]	t_{IST} [h]
A	12,754.7	2,352
C	215,112.9	8,745
U	69.0	10
V	64.2	9
W	64.0	9

It can be concluded that the implemented control strategy, which regulates the supply pressure difference between both heat sources (see Fig. 8) in such a way that the required mass flows for the specified heat supply is complied (see Fig. 9), is suitable for the simulated case study.

4.2. Reference simulation of FZJ district heating system

To evaluate the effects of waste heat integration, we first simulate the current district heating system with only one heat source as a status quo, i.e. Ref_0. In Fig. 10, the pipes in the network structure with higher specific pressure losses than 250 Pa/m, so-called bottlenecks, are marked in orange. Furthermore, the critical buildings that receive temporary too low supply temperatures are highlighted and labelled.

There are four bottlenecks in the network structure in the current district heating system, supplied by one central heat source. However, the pipe segments where these bottlenecks occur are quite short (see Fig. 10), which only leads to low absolute pressure losses.

Table 2 summarises the critical buildings that are insufficiently supplied with their calculated IST and the summed up time duration with insufficient supply temperatures t_{IST}. The critical buildings are named alphabetically in this study to facilitate comparison between the simulation scenarios carried out.

In the reference simulation, five critical buildings are identified north of the campus (see Fig. 10 and Table 2). As the affected buildings are far away from the heat supply source, the occasionally low supply temperatures are not surprising, as high cooling rates occur due to the long distribution distance. The three buildings in a side branch of the network (U, V, W) are affected by insufficient supply for 9-10 h a year with a temperature difference of around 7 K, resulting in IST from 64 K h to 69 K h. However, the two other buildings, A and C, have much higher IST values, indicating a more critical insufficient supply. Building A on the campus has a IST of 12,755 K h, which is due to excessively low temperatures averaging 5 K over a combined period of about 100 d. The heat demand of building A is relatively low compared to the other buildings, which leads to small mass flow rates and, due to the large installed pipes, to small fluid velocities. This results in high cooling rates and, thus to too low supply temperatures at building A. In reality, the insufficient supply of the shown critical buildings is managed, for instance, by individual control strategies of the heating systems or by adapting the district heating curve.

Building C on the FZJ campus represents a backup connection to the small low-temperature district heating system mentioned above [31]. In the simulation model, the heat demand of building C is set to a minimum demand to maintain a minimum mass flow circulation for simulation stability. However, due to the minimum mass flow and the large installed pipe diameters to this backup connection, the cooling rates in this pipe are quite high resulting in a high temperature drop and thus to the high IST of building C. However, since the insufficient supply results from how this backup connection is modelled, the critical supply of this particular building is negligible. In the following, the IST values of building C are not listed anymore in the result tables of the other simulation scenarios.

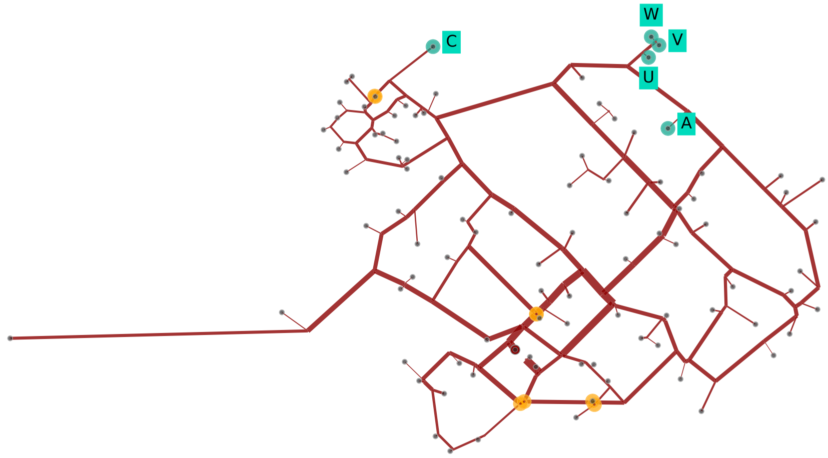

Fig. 10. Highlighted bottlenecks (orange) and labelled critical buildings (turquoise) in the district heating network for reference simulation Ref_0.

4.3. Effects of waste heat integration into the FZJ district heating system

We first show the effects of different waste heat shares supplied by the additional heat source at the current high supply temperatures. Following, we analyse the impact of reducing the supply temperature.

4.3.1. Different waste heat shares

The bottlenecks in the network for three different shares of waste heat integration without adaption of the current high supply temperatures (HT_{20}, HT_{30}, HT_{40}) are visualised in Fig. 11, 12, 13. The critical buildings in the network are highlighted.

Waste heat integration at a high temperature level does not lead to any additional bottlenecks in the network. In contrast to the four bottlenecks identified in the reference case, only one bottleneck is remaining in the northwest of the network for all three scenarios. The value of the specific pressure losses at this bottleneck even decreases with increasing waste heat share in the network from 561 Pa/m in Ref_0 case to 425 Pa/m in HT_{40}.

Several critical buildings that receive temporary too low temperatures can be identified. The critical buildings and their calculated IST as well as the summed up time duration with insufficient supply temperatures t_{IST} are summarised in Table 3.

Neglecting the insufficient supply of building C (see. Section 4.2), the previously identified buildings in the north of the campus (A, U, V, W) are now sufficiently supplied when the waste heat is integrated. This results from the fact that heat at high temperatures is supplied in the north of the network and unfavourable mass flows in this area of the network do not occur anymore.

Additional critical buildings are identified in the district heating system for waste heat integration. The locations in the network structure where the critical buildings arise change with different waste heat shares in the network. In HT_{30}, only building B, I and K are critical, but in HT_{20}, additionally building R and L are insufficiently supplied. In HT_{40}, the same buildings occur as in HT_{30} but additionally building O, M and P are affected by temporary too low supply temperatures. The changed locations of critical buildings in the network result from the changed mass flow conditions in the network. Since in HT_{40} much more mass flow is integrated at the additional heat source than in HT_{20}, the unfavourable mass flow rates or dead mass flow points, which lead to low flow velocities and thus to high cooling rates, occur in different parts of the network and therefore other buildings are affected.

Most of the identified critical buildings are only insufficiently supplied during a few hours a year and have an IST below 10 Kh (see Table 3). However, in each waste heat share scenario, there is at least one building with a much higher IST, indicating a more critical insufficient supply. Building I and K have high IST values for all waste heat shares, but they differ due to the different mass flow conditions in the network. Building B is only minorly affected by insufficient supply for 20% or 30% waste heat share (4.6 Kh and 5.4 Kh), but for 40% waste heat share the insufficiently supply is higher and occurs during a longer time period (434.2 Kh and 111 h).

4.3.2. Medium supply temperatures

Reducing the supply temperatures in the district heating system leads to lower heat losses and to higher mass flows in the network, since the temperature difference between supply and return decreases.

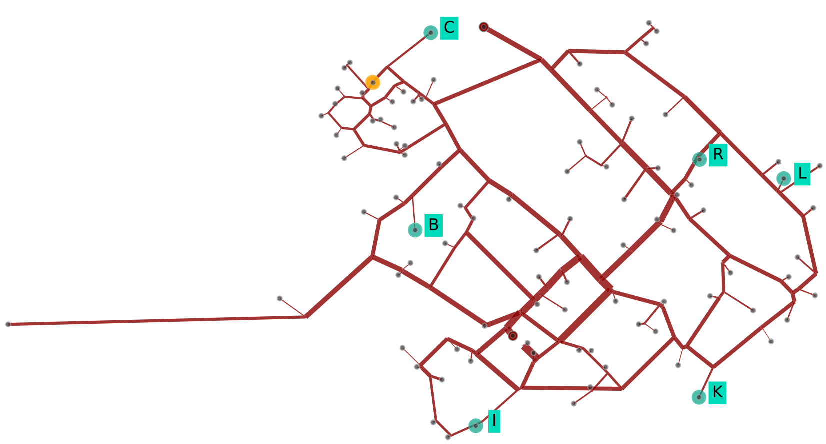

Fig. 11. Highlighted bottlenecks (orange) and labelled critical buildings (turquoise) in the district heating network for scenario HT_{20}.

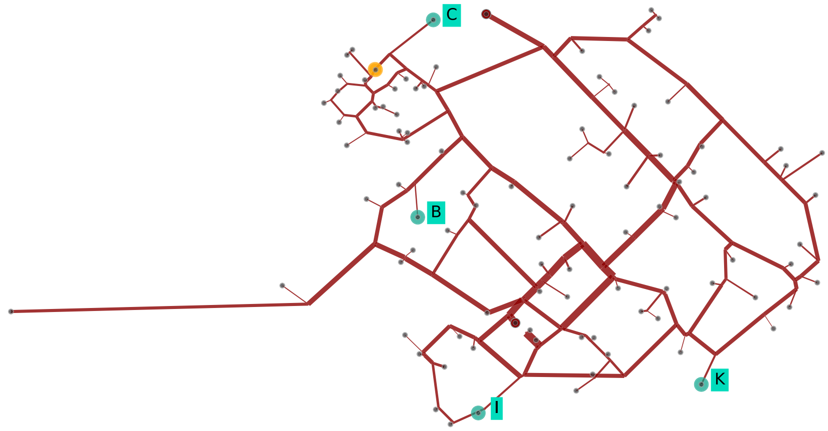

Fig. 12. Highlighted bottlenecks (orange) and labelled critical buildings (turquoise) in the district heating network for scenario HT_{30}.

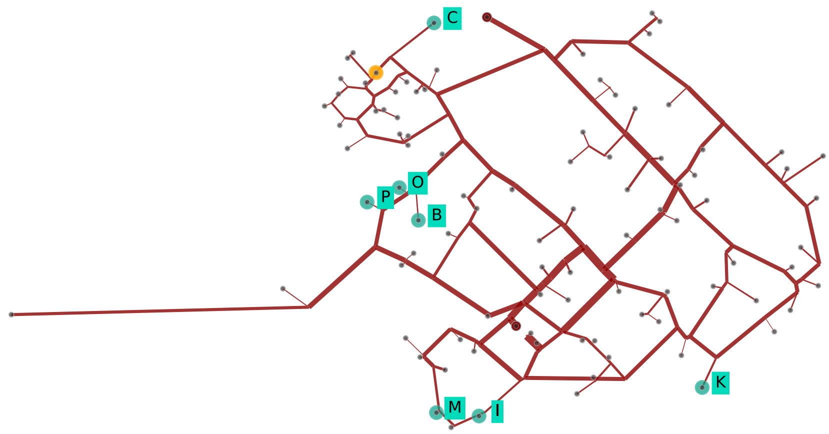

Fig. 13. Highlighted bottlenecks (orange) and labelled critical buildings (turquoise) in the district heating network for scenario HT_{40}.

Table 3
IST of critical buildings and time duration of insufficient supply t_{IST} for different waste heat shares in the district heating system, operating at high supply temperatures.

	HT_{20}		HT_{30}		HT_{40}	
Building	IST [K h]	t_{IST} [h]	IST [K h]	t_{IST} [h]	IST [K h]	t_{IST} [h]
B	4.6	3	5.4	4	434.2	111
I	401.0	53	82.8	12	183.5	41
K	95.2	39	118.1	46	141.6	46
L	7.1	13	-	-	-	-
M	-	-	-	-	9.7	6
O	-	-	-	-	0.2	1
P	-	-	-	-	4.7	2
R	0.9	1	-	-	-	-

The heat losses reduce on average from 18.4% in the HT-scenarios to 16.4% in the MT-scenarios, which means a relative heat loss reduction of around 10%.

The operating conditions in the network change due to the reduced supply temperatures and the corresponding rising mass flows. In Fig. 14, 15, 16 the bottlenecks and the critical buildings are highlighted for all three waste heat shares with reduced supply temperatures (MT_{20}, MT_{30}, MT_{40}).

The increased mass flows lead to additional bottlenecks in the network for all studied waste heat shares compared to the waste heat integration at high supply temperatures (HT_{20}, HT_{30}, HT_{40}). In MT_{20} and MT_{30}, four additional bottlenecks arise compared to the HT-scenarios that are distributed over the entire network. In MT_{40}, only three additional bottlenecks are identified. The locations of the bottlenecks within the network are independent from the waste heat shares. In contrast, the height of pressure losses that occur is not independent from the waste heat shares. If the bottlenecks occur for several examined waste heat shares, the size of pressure losses can be higher, lower, or in the same order of magnitude for rising waste heat shares. The changing extent of pressure losses results from the different mass flow conditions in the network, depending on the integrated mass flow at the decentralised heat source. Therefore, it can be said that more bottlenecks arise in the network at reduced supply temperatures, but the height of pressure losses is specific to the amount of waste heat that is integrated.

Table 4 lists the critical buildings for all simulation scenarios with reduced supply temperatures. In general, it can be seen that more buildings are affected by insufficient supply when the supply temperatures are reduced. However, the location and IST of the critical buildings

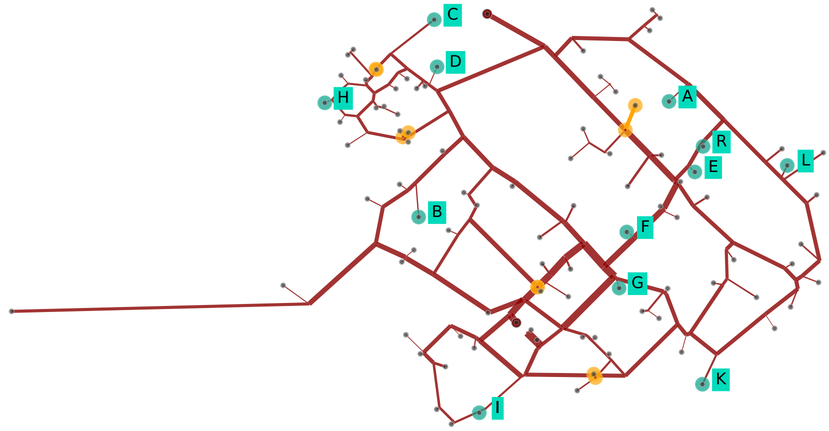

Fig. 14. Highlighted bottlenecks (orange) and labelled critical buildings (turquoise) in the district heating network for scenario MT_{20}.

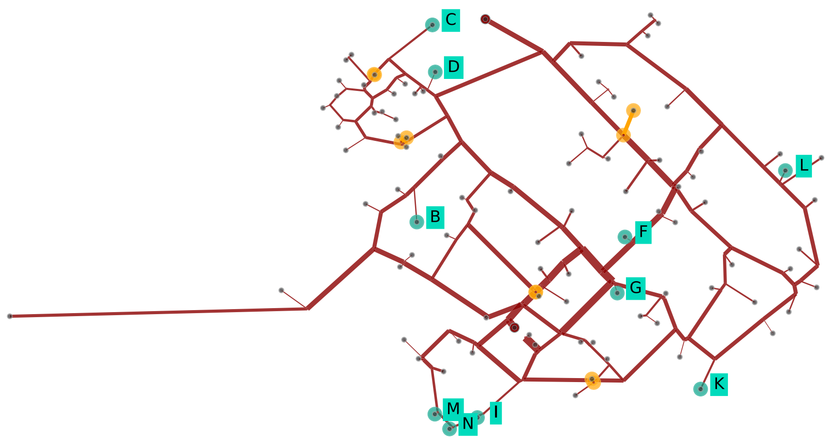

Fig. 15. Highlighted bottlenecks (orange) and labelled critical buildings (turquoise) in the district heating network for scenario MT_{30}.

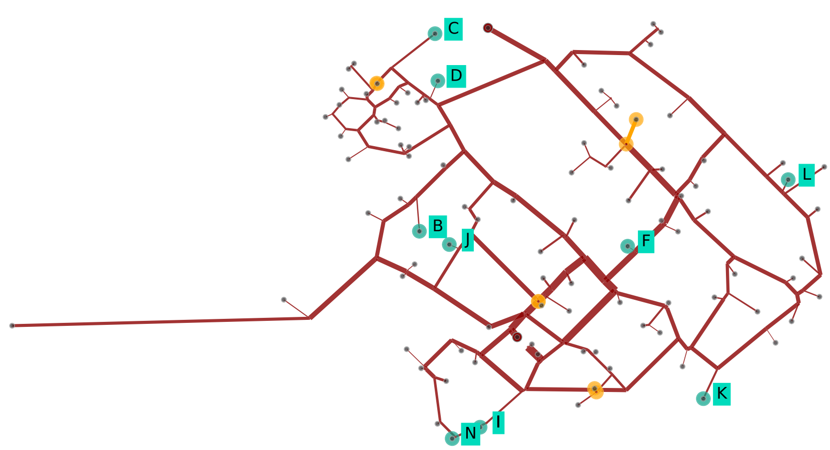

Fig. 16. Highlighted bottlenecks (orange) and labelled critical buildings (turquoise) in the district heating network for scenario MT_{40}.

Table 4
IST of critical buildings and time duration of insufficient supply t_{IST} for different waste heat shares in the district heating system, operating at reduced supply temperatures.

	MT_{20}		MT_{30}		MT_{40}	
Building	IST [K h]	t_{IST} [h]	IST [K h]	t_{IST} [h]	IST [K h]	t_{IST} [h]
A	1.4	4	-	-	-	-
B	225.0	93	262.7	97	780.4	213
D	6.6	7	5.3	5	5.3	5
E	743.02	225	-	-	-	-
F	15.2	12	15.0	12	15.6	12
G	5.2	8	3.7	4	-	-
H	1.2	3	-	-	-	-
I	756.1	109	141.0	26	588.7	124
J	-	-	-	-	3.8	1
K	550.1	119	593.7	120	646.8	127
L	370.3	130	88.3	49	16.2	17
M	-	-	43.9	3	-	-
N	-	-	52.3	5	6.4	1
R	153.2	33	-	-	-	-

depend on the amount of integrated waste heat as the mass flow conditions in the network change. Most of the critical buildings identified in the scenarios with high supply temperatures are also supplied insufficiently in the scenarios with reduced supply temperatures. Furthermore, the IST values of these critical buildings and the time duration of insufficient supply are higher than before. For example, the critical buildings B, I, and K have much higher IST values than in the scenarios with higher supply temperatures (compare Table 3), since primarily the duration of insufficient supply are higher when the supply temperatures are reduced. Therefore, reducing the supply temperatures in the district heating system leads to additional critical buildings and also to higher extent of insufficient supply, whereby the location of critical buildings and actual level of insufficient supply depend on the integrated amount of waste heat.

5. Discussion

5.1. Waste heat integration at the FZJ district heating system

Based on the simulation results, the waste heat integration at the FZJ district heating system is technical feasible for waste heat shares up to 40% while maintaining current supply temperatures. However, due to the temporarily insufficient supply to some buildings, more detailed investigations of network operation and mass flow conditions within the pipe structure have to be carried out to avoid under-supply of any building.

When reducing the supply temperatures in the district heating system the operating conditions are getting worse. The increasing mass flows in the network create additional bottlenecks and more buildings are supplied insufficiently and for longer times. Reducing the supply temperature therefore requires additional measures to ensure a feasible operation. However, the difficulties in network operation due to reduced supply temperatures are not influenced by the realised waste heat integration, as the number of arising bottlenecks and critical buildings is independent on average for all simulated waste heat shares.

The temporary insufficient temperature supply to critical buildings could be resolved by temperature boosting at the critical time periods, either centrally at the heat sources or locally at the critical consumers with heat pumps or electrical heaters. Alternatively, the mass flow conditions in the network could be controlled more precisely by using additional decentralised circulation pumps to avoid areas in the network with disadvantageous mass flow conditions. Since at reduced supply temperatures the bottlenecks show higher specific pressure losses and also longer pipe segments are affected, a replacement of affected pipes must be considered to avoid high energy costs for the circulation pumps.

Another possibility to mitigate effects of reducing the supply temperatures could be the simultaneous reduction of the return temperature. However, a reduction of the return temperature in the network requires additional measures on some heating systems to cope with such temperatures at the substations.

Adjustments to the heating systems on the secondary side of the substation can significantly contribute to reducing the overall district heating supply temperature. The measures on the existing buildings to enable the supply with reduced supply temperatures can be the renovation of the buildings, the replacement of the critical radiators, or the optimisation of the implemented weather compensation curve of the heating systems [32,33]. Therefore, the following investigation steps should be the evaluation of different measures to reduce the temperature requirements of the identified critical buildings to improve waste heat integration at low supply temperatures.

5.2. Extension by optimisation approach

In this study, it is anticipated that the same heating curve is applied in each building. A more precise analysis of the different temperature requirements of the supplied buildings could increase the efficiency of heat distribution. Since in reality not every building requires the same supply temperature, also lower supply temperatures should be sufficient for some areas of the district heating system. To unlock the potential of more accurate supply temperature matching to the specific requirements of the buildings, a cascade heat pump configuration could be set up in the network. For example, the temperature raised by a central heat pump may be below the maximum temperature requirement of the worst building in the network, but still be sufficient for most other buildings. For the buildings with the highest temperature requirements, the previously mentioned measures can help to reduce the required temperatures, or additionally installed decentralised heat pumps could further increase the temperature to a sufficient level.

To determine the optimal central temperature level, an optimisation approach could be developed to determine the optimal design of heat pump installation and operating temperatures depending on the actual requirements of the supplied buildings.

6. Conclusion

The decarbonisation of existing district heating systems by substituting fossil-based heating plants with sustainable heat sources is essential for a carbon neutral heat supply in the buildings sector. Such heat supply substitution is planned on the FZJ campus, as the waste heat from an upcoming HPC should be integrated into the local district heating system to reduce the supply of the current gas-based heating plant. In this paper, we test the feasibility of the waste heat integration into the existing district heating system by means of simulations, whereby the model from previous work is extended to consider multiple heat sources in a district heating system.

The evaluation of the simulation model shows a correct behaviour and control strategy, and can therefore be used to investigate the feasibility of waste heat integration into the local district heating system of the FZJ campus.

Different simulation scenarios are carried out to evaluate the effects of varying waste heat shares in the network and, in addition, to examine the possibility of reducing the supply temperature in the network. The results show that a waste heat share up to 40% in the network is feasible. However, small measures are necessary to avoid the insufficient supply of some consumers. Reducing the supply temperatures leads to additional bottlenecks and more consumers are affected by insufficient heat supply. These issues can be mitigated by pipe exchanges, integration of decentralised circulation pumps or partial temperature boosting. The simulation is already applicable for the investigation on the benefits of such measures. These measures and the renovation of selected buildings in the network are subject to future work.

Overall, the simulation study and the model prove as a practical use-case to investigate the main effects of waste heat integration, as such utilisation of sustainable heat sources will become more common in existing district heating systems and prior identification of network operation difficulties is essential for such projects.

Nomenclature

Abbreviations

CCHP	Combined Cooling, Heat and Power
CHP	Combined Heat and Power
FZJ	Forschungszentrum Jülich
HPC	High Performance Computer
HT	High Temperature Scenario
MT	Medium Temperature Scenario
Ref	Reference Scenario

Symbols

Δ	Difference, -
IST	Insufficient Supply Temperature, K h
i	Index of Summation, -
$\dot{m}$	Mass Flow, kg/s
n	Upper Limit of Summation, -
p	Pressure, Pa
$\dot{Q}$	Heat Flow, W
q	Heat Ratio, %
T	Temperature, K
t	Time, s

Subscripts

add	Additional Heat Source
HX	Heat Exchanger
main	Main Heat Source
req	Required Temperature at Heating System of Building
return	Return Line of District Heating
supply	Supply Line of District Heating

CRediT authorship contribution statement

Jan Stock: Conceptualization, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Felix Arjuna:** Methodology, Software, Visualization, Writing – review & editing. **André Xhonneux:** Funding acquisition, Project administration, Resources, Supervision, Writing – review & editing. **Dirk Müller:** Funding acquisition, Project administration, Resources, Writing – review & editing.

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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