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# Optimisation of district heating network separation for the utilisation of heat source potentials

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ABSTRACT

Integrating sustainable heat sources into district heating systems is crucial to reduce the mainly fossil-based heat supply in the building sector. However, integrating a heat source into an existing district heating system can be challenging due to non-matching temperature levels or unfavourable availability of the heat source intended for utilisation. To avoid the problems associated with heat source integration, i.e. utilisation in an existing district heating system, an alternative approach is to separate the district heating network into two independent networks. Thus, the separated network forms a standalone district heating system, which is supplied by the utilised heat source and can be individually transformed depending on the characteristics of the utilised heat source and the supplied buildings. In this way, complex design and control adaptions for the entire district heating system are avoided.

This work presents a method for the automatic determination of optimal district heating separation depending on the given district heating network structure and the heat source that should be utilised. For this purpose, an optimisation model determines the separation based on predefined coherent areas in the network, while considering the potential of the heat source and the heat requirements of the buildings. The application of the presented method shows various network separations depending on the heat source conditions and the focused optimisation objectives. The subsequent network simulation identifies critical areas for insufficient heat supply from which various necessary measures could be derived.

## 1. Introduction

The decarbonisation of the building sector is an important part of the energy transition towards climate neutrality. In the building sector, where most energy is consumed to provide thermal comfort, the replacement of fossil-fuel based heating systems is essential for a sustainable heat supply. For this purpose, several sustainable heat source potentials are available locally, such as waste heat from various processes [1,2] or geothermal heat [3,4]. The use of locally available heat sources to supply buildings is possible with district heating (DH) systems, which distribute the heat via pipe networks. Currently, most European DH systems are still supplied by fossil-based heating plants [5] and are operated at high supply temperatures and therefore can be classified as 2nd or 3rd generation of DH systems [6]. Therefore, the current outdated DH infrastructure must be transformed to reduce carbon dioxide emissions and to achieve more efficient heat distribution.

Essential elements of the DH transformation process are summarised in [7], such as the integration of renewable energy sources, the reduction of DH return and supply temperatures or the necessary building adaptions to cope with lowered supply temperatures. However, different barriers can arise during the transformation process, e.g. reduced supply temperatures in the existing pipe network can result in too high mass flows and correspondingly high pressure losses, which can impair the sufficient heat supply to the connected buildings [8]. Especially the integration of sustainable heat sources into existing DH systems can be challenging, as the temperature level of an available heat source often does not match the DH temperatures or the geographical location is unfavourable concerning the given network structure. In the following, we give an overview about different challenges that arise in the context of heat source utilisation in existing DH networks and the transformation of DH systems.

The integration of decentralised heat source into an existing DH network leads to changed mass flow conditions in the pipes [9,10]. Both the magnitude and the direction of the mass flow in the pipes change,

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as the amount of supplied heat increases in a part of the network. The changed flow rates due to decentralised heat source integration can also result in fluctuating thermal stresses in the pipes [9]. Nord et al. also showed that an additional heat source can lead to pressure cones in the network that affect the reliable heat supply to some consumers in the network [11]. Arising bottlenecks and insufficiently supplied buildings resulting from the integration of an additional waste heat source into an existing DH system in conjunction with a reduction of the supply temperature are also shown in [10]. Therefore, the additional integration of heat sources requires network control adaptions to avoid unfavourable pressure conditions and to prevent buildings from being insufficiently supplied [12,13].

Since most sustainable heat sources for utilisation are only available at low-temperature levels, an essential part of DH transformation is the reduction of current supply temperature levels to enable the efficient integration and distribution of these heat potentials. However, the minimum temperature requirements of the heating systems in the buildings must be met to cover the heat demand of the users. As outlined by Guelpa et al. many existing buildings supplied by DH can already cope with lowered supply temperatures without active measures, as components, e.g. substations or heaters in the rooms, are often oversized and can therefore compensate for reduced supply temperatures [14]. Furthermore, fault detection and correction at the substations within the DH system can help to exploit the potential for lowering supply temperatures without extensive measures [14,15]. However, a great DH temperature reduction requires measures at the supplied buildings, such as replacing critical heaters within the buildings [7,16] or reducing the heat demand, e.g. by refurbishing the buildings [14]. Alternatively, the installation of decentralised heat pump (HP) systems in the buildings with the highest temperature requirements can help to reduce the overall DH supply temperature even further, as most critical temperature points in the network are decoupled and managed by individual temperature boosting [7,14].

Overall, additional heat source integration and DH temperature reduction requires the investigation of all supplied buildings and the derivation of necessary measures to ensure a sufficient supply despite the changed DH operating conditions. This makes the transformation process quite extensive, especially for large DH systems, since the effort and the number of required measures increases with the number of buildings.

### 1.1. Decentralisation of existing district heating networks

Many difficulties concerning heat source utilisation described above result from the design of current DH systems that are mostly centralised supplied and were not designed to integrate decentralised heat sources. In addition, mass flows, i.e. the pipe diameters, and temperature levels were designed according to the most critical buildings in the network, although the requirements of the buildings in the network are often very different.

Decentralising these centrally organised DH systems can help to efficiently utilise smaller and locally available heat source potentials and thus replace the large heating plants currently in operation. In addition, decentralisation, i.e. the separation of the DH network, means that the resulting DH systems can be adapted much more specifically and precisely to the new supplying heat sources and the requirements of the supplied buildings. The main advantage of this approach is the mitigation of barriers that arise when integrating a heat source into the holistic DH system, e.g. the challenging hydraulics or the temperature balance as described in literature before. By focusing on the transformation process of the separated network segment, the required measures at the network structure or supplied buildings can be identified with less investigation and implementation effort in comparison to transforming the entire existing DH system. However, since there are many potential candidates for separation, it is challenging to determine the most advantageous network separation based on the characteristics of the heat source intended for utilisation and a given DH system to achieve the highest possible utilisation rate. Thus, both the size and the transformed design of the separated network must be optimised to achieve a high utilisation rate while maintaining an efficient and reliable heat supply.

In [17], the idea of dynamically distributed existing DH systems is presented, in which network areas are partially disconnected and operated in island mode during the heating period. Through this approach, the different network areas could be transformed more individually. However, no general method for determining optimal areas for disconnection or separation is presented. A total separation into two DH networks is presented by [18]. In this case study, an available waste heat source of a high-performance computer is utilised by separating buildings and pipes from an existing DH network to establish a standalone DH system, which is operated at much lower temperature levels than the remaining network. To ensure sufficient heat supply, decentralised HPs are installed in the supplied buildings for temperature balancing. However, the buildings to be separated were manually selected based on their location in the vicinity of the high-performance computer. A generic approach to identify buildings or coherent areas within the network structure for network separation in an automated way is not pursued.

In general, the identification of coherent areas within a distribution network is a widely used approach, not yet to separate existing network structures, but for instance to improve control strategies. Methods to identify coherent areas in a network structure, i.e. clusters or communities, are called clustering or community detection algorithms [19]. For instance, community detection algorithms are used in water distribution networks to identify district-metered areas, which are sectorised by installing valves and flow meters, to detect leakage in the network fast and precisely [20]. In the context of DH, the identification of coherent network areas is already used either to identify consumer groups [21] or to analyse spatial distributions of buildings to identify potential areas for DH construction [22,23]. Zhong et al. identify coherent areas in a DH network structure that could be separated by valves and circulation pumps to improve the control of heat distribution [24]. In [25], an aggregation method is used to group multiple buildings in a DH network into one consumer node to estimate the storage and demand side management potentials of aggregated areas within large DH networks.

Community detection algorithms can also be used to identify coherent areas in a network that are advantageous for separation in order to decentralise large DH networks. In our previous work, the idea of DH separation in combination with community detection is already formed into an holistic approach for automated DH separation [26]. In this work, we focused on the detection of all possible network separations based on the identified community structure and evaluated each possibility individually through network simulations and an economic and environmental assessment. Therefore, the presented approach in [26] represents a computationally intensive approach. In addition, the DH design of the separated network in [26] is predefined for the simulations and therefore not optimally adapted to the utilised heat source and the given building characteristics.

### 1.2. Contribution

The advantages of decentralising existing DH systems to facilitate the utilisation of sustainable heat sources [17,27] or to enable a simplified step-wise transformation [17,18] were already demonstrated. However, these studies do not present a generic approach that reveals the optimal separation for achieving the decentralisation of existing DH networks, taking into account the given conditions of the network structure and supply requirements. Although the described work of [26] fills this gap to a certain extent, the following points need to be addressed: (i) determining the optimal DH network separation, (ii) limiting the computational expenditure, and (iii) determining the optimal DH transformation based on the available heat source and the requirements of the buildings supplied.

The present work aims to develop a more efficient approach in terms of computational effort to determine the most advantageous DH separation by substituting the simulative approach used in [26] with a mathematical optimisation model. In addition, this approach makes it possible to determine the transformed design of the separated DH system depending on the separated network and the utilised heat source, as optimisation models are widely used to optimise the design and operation of DH systems [28–31].

Starting from the identification of communities in a DH network, we develop an optimisation model to determine the optimal separation of an existing DH network to utilise an available heat source in the separated network while the remaining network is not adapted and still supplied by the current heating plant. We apply the developed optimisation model to a use case to show the performance of the model and the fast adaption with respect to different boundary conditions such as the heat source capacity or its location. Finally, the determined optimal DH network separation is evaluated concerning a practicable DH operation by simulating and analysing both resulting DH systems.

The paper is structured as follows: Section 2 introduces the overall approach to determine the optimal DH separation. The model is applied to a use case in Section 3, where the results are presented for two considered optimisation objectives. Subsequently, the results and the developed model are discussed in Section 4 while Section 5 summarises this work.

## 2. Methodology

First, we introduce the community detection algorithm that is used to identify coherent areas in an existing network structure. We then present the optimisation model that determines the optimal network separation. Finally, evaluation steps for a feasible network separation are presented.

### 2.1. Community detection

By representing a network as a graph, community detection algorithms can identify coherent areas within the graph structure, i.e. communities. To evaluate the identified community structure, the quality function modularity is used. Modularity compares the identified community structure in a graph with a so-called null model of this graph, which is assumed to have no community structure at all. The maximisation of modularity thus identifies the optimal community structure in the graph, i.e. the network structure under investigation [19].

As in our previous work [26], we use the Girvan–Newman algorithm [32] to identify communities in the investigated DH network. The Girvan–Newman algorithm identifies the communities in the network structure based on weighting the edges between the nodes. For each possible node pair combination, the shortest path along the edges is calculated. If an edge is passed by such a shortest path, the weight of the edge is increased by one. After all edges in the network are weighted for all node pair combinations, the edge with the highest weight is removed to reveal the first communities. This approach is repeated iteratively until each node represents a community and the entire graph can be represented as a hierarchical community tree [32]. Finally, the identified community structure that achieves the highest modularity is selected as the optimal community structure. Since the approach of the algorithm is based on edge removal to identify communities, it is beneficial for the intention of separating coherent network areas.

To apply the Girvan–Newman algorithm to a DH network, the network must be represented as a graph structure, with the edges symbolising the DH pipes and the nodes the supplies, consumers and junctions of the network. Since the branching sections in the graph are important for identifying communities, the DH network should be represented as a simplified graph structure, whereby e.g. expansion loops or curved courses in the network structure are neglected. Such unimportant network patterns are represented as several edges in a pipe section without junctions, i.e. edge sections that only contain nodes connecting two edges. Therefore, pipe sections that consist of multiple pipes but do not contain branching pipes are simplified and represented as one edge between two junction nodes of the graph, as shown in Fig. 1.

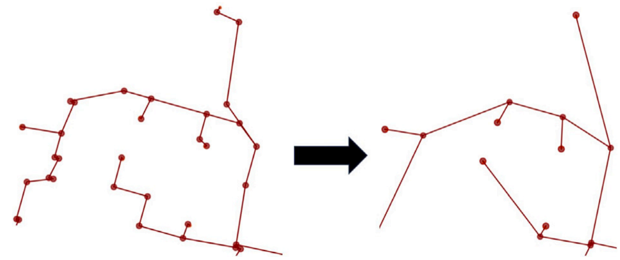


**Fig. 1.** Example of simplifying the graph representation of a DH network.

### 2.2. Optimisation model

The identified communities by the Girvan–Newman algorithm are used in the optimisation model. The developed optimisation model is based on a two-stage optimisation, i.e. the optimisation of the design takes into account the operational optimisation of the most important operating points, using the component-oriented modelling and optimisation framework COMANDO [33].

The model scheme of the DH system is shown in Fig. 2. The heat sources are labelled as old heat source (OHS), representing the current heating plant that still supplies the remaining network, and new heat source (NHS), representing the utilised heat source that supplies the separated network. $\mathrm{Com}_{1,2,\ldots,i}$ represent the identified communities, which consist of a sub-network (NET) with its connected consumers $\mathrm{c}_{1,2,\ldots,j}$. The grey boxes represent the optional design components of the DH system. An optional HP can be installed for each consumer to raise the temperature individually. Either a central HP or a heat exchanger (HX) is installed at the new heat source. Each optional HP is connected to the power grid (PG). $\mathrm{b}_{\mathrm{new}}$ and $\mathrm{b}_{\mathrm{old}}$ are the connection decisions that represent the option to whether a community is supplied by the old or new heat source. Therefore, $\mathrm{b}_{\mathrm{new}}$ refers to the separated DH network and $\mathrm{b}_{\mathrm{old}}$ to the remaining network. The two arrow routes shown in red and orange therefore represent the optional connection to the corresponding heat source. The connection between the two arrow routes symbolises an optional peak load supply of the remaining DH system to the separated DH system. The different components are described in 2.3.

#### 2.2.1. Separation through connection decision

Each community consists of a sub-network comprising the corresponding pipes of the network area and its connected consumers. These sub-networks are coupled to each heat source by a connection decision, one to the old $\mathrm{b}_{\mathrm{old}}$ and one to the new heat source $\mathrm{b}_{\mathrm{new}}$ (see Fig. 2). Thus, it is optional for each community in the network to be connected to the new heat source, i.e. to be part of the separated DH network, or to be connected to the old heat source, i.e. stay as part of the remaining DH network.

The connection decision is represented as design variable $b$ that determines whether the connection is built ($b = 1$) or not ($b = 0$). Since not both heat sources should supply one community, a constraint is implemented for each connection pair to ensure that only one connection is realised for each community.

$$b_{\mathrm{old},i} + b_{\mathrm{new},i} \leq 1 \quad \forall i \in n_{\mathrm{Com}} \tag{1}$$

As the heat demand of all consumers in each community must be covered, one of the two connection decisions is automatically set to one

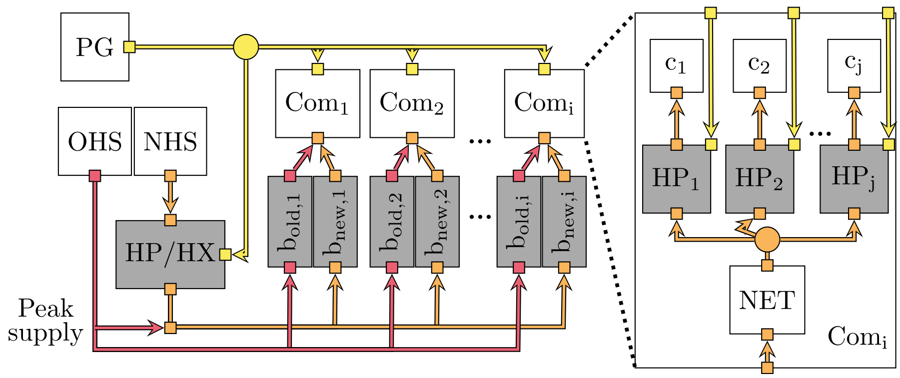



**Fig. 2.** Schematic representation of the DH system optimisation model. The heat sources OHS and NHS supply the communities $\mathrm{Com}_{1,2,\ldots,i}$ that consist of a DH sub-network NET and its connected consumers $c_{1,2,\ldots,j}$. HP and HX are optional components for installation and $b_{old/new}$ are the connection decision for DH separation. The PG supplies the optional HP systems.

to maintain the energy balance. Constraint (2) ensures that at least one community is separated from the network.

$$\sum_{i=1}^{n_{\mathrm{Com}}} b_{\mathrm{new},i} \geq 1 \tag{2}$$

### 2.2.2. Realisable community combinations for separation

One or multiple communities can be separated from the DH network. However, some combinations of communities are non-sensible for separation. We have to ensure that only neighbouring communities are separated, as only a coherent area enables a standalone DH system without the need to install additional pipes. In addition, it must be ensured that each DH network is connected to a supplying heat source, i.e. a DH network with one existing heating plant and one heat source intended for utilisation can only be separated into two networks. Therefore, each possible combination of communities must be checked in this regard.

Each community can be either part or not part of the separated network. This means that $2^{n_{\mathrm{Com}}} - 1$ combinations of communities must be tested since individual communities but also combinations with all other communities represent separation possibilities. Each combination of communities is checked for two aspects. First, it is checked whether the communities are neighbouring to ensure that a coherent DH network is separated. Second, we check whether all remaining network nodes are still connected to avoid creating more than one remaining DH network. If the tested combination of communities is realisable for separation, the combination is added to a set of realisable combinations.

For each identified realisable combination of communities, a design variable $b_{\mathrm{sep},k}$ represents the separation of this specific combination $k$ from the network. The constraint (3) is set for each realisable combination $k$. Constraint (3) represents the design variables of all community connection decisions $\mathrm{b}_{\mathrm{old}}$ and $\mathrm{b}_{\mathrm{new}}$ according to the realisable combination $k$:

$$\sum_{i=1}^{n_{\mathrm{Com}}} b_{\mathrm{old/new},i} \geq b_{\mathrm{sep},k} \cdot n_{\mathrm{Com}} \tag{3}$$

$b_{\mathrm{old/new},i}$ represents the connection variable $b_{\mathrm{new}}$ or $b_{\mathrm{old}}$ that is used for the corresponding community in the realisable combination of communities $k$ to indicate whether this specific community belongs to the separated or the remaining network. For the communities that are part of the combination $b_{\mathrm{new}}$ is summed up, and for communities that are not part of the combination $b_{\mathrm{old}}$ is added to the sum. Therefore, the left side of constraint (3) represents the decision variable of each community, which must be one with regard to the realisable community combination $k$.

The right side of constraint (3) represents the realisation of the realisable combination $k$, as the decision variable $b_{\mathrm{sep},k}$ is multiplied by the total number of communities $n_{\mathrm{Com}}$. Therefore, the realisable combination $k$ is selected by the optimisation if $b_{\mathrm{sep},k} = 1$, as only then the constraint is fulfilled and the corresponding communities are selected for connection to the new separated DH network, while the other communities are connected to the remaining DH network.

Since only one realisable combination can be separated, the sum of all realisable combination design variables $b_{\mathrm{sep},k}$ must be one

$$\sum_{k=1}^{n_{\mathrm{combi}}} b_{\mathrm{sep},k} = 1. \tag{4}$$

The realisable combinations are also used to consider the costs for a connection pipe between the separated network and the new heat source. The costs are calculated specifically for each realisable combination of communities and linked to the design variable $b_{\mathrm{sep},k}$. The cost of constructing a DH pipe is determined by its length and diameter. The length is calculated based on the shortest possible connection path along the pipes already installed, as no street data is available. The pipe diameters is determined based on engineering guidelines as the nominal supply is known through the included buildings in the respective communities.

### 2.2.3. Supply constraint for separation

The communities and associated buildings intended for separation are selected based on the available heat source capacity and the temperature conditions in the DH system, i.e. the requirements of the buildings and the available temperature level of the heat source. However, an energy balance of the DH system shows that the optional installation of HP systems (see 2.3.2) for temperature balancing represents an external energy supply for the separated DH system, i.e. the power supply for HP operation is an additional energy supply. The separated DH network is mainly supplied by the utilised heat source and the peak supply through the remaining network. As a central HP uses the heat from the utilised heat source and supplies it into the DH network, and decentral HPs use the heat from the DH network and supply the buildings, the power used to operate the HPs is additional supplied energy to the DH system.

The utilised heat sources are generally low-emissions or low-cost, so their use is maximised by the optimisation. The discrete separation possibilities, predefined by the identified communities, usually do not match the available heat capacity. Therefore, HPs could be installed as additional energy supply options to extend the peak supply capacity and thus allowing the selection of a larger separation option.

In reality, HP systems are not built as peak load systems but to supply the baseload and raise the supply temperature. In addition, the considered peak supply option through the remaining network (see 2.3.5) offers the possibility to supply the peak loads that exceed the heat capacity of the utilised heat source, e.g. to separate network areas with heat demands that slightly exceed the available thermal capacity at nominal loads. Therefore, the possibility of the optimisation model to install HPs as an additional energy supply option must be constrained to avoid non-realistic design solutions. To prevent the installation of HPs for the intention of additional energy supply, the maximum heat supply to the separated DH network $\dot{Q}_{\mathrm{net,sep,tot}}$ is constrainted by

$$\dot{Q}_{\mathrm{net,sep,tot}} \leq \frac{\dot{Q}_{\mathrm{source,max}}}{1-\epsilon_{\mathrm{peak}}} \tag{5}$$

with the maximal capacity of the utilised heat source $\dot{Q}_{\mathrm{source,max}}$ and the fraction of heat supply which is permitted through the remaining network $\epsilon_{\mathrm{peak}}$ (see 2.3.5). By this, the power supply to the HPs is restricted as it is included in $\dot{Q}_{\mathrm{net,sep,tot}}$, which is calculated according to

$$\dot{Q}_{\mathrm{net,sep,tot}} = \dot{Q}_{\mathrm{source}} + P_{\mathrm{el,HP,cen}} + \dot{Q}_{\mathrm{peak}} + \sum_{c}^{C} P_{\mathrm{el,HP,dec,c}}, \tag{6}$$

where $\dot{Q}_{\mathrm{source}}$ is the actual used heat supply by the heat source, $P_{\mathrm{el,HP,cen/dec}}$ symbolise the power supply to all central and decentral HPs and $\dot{Q}_{\mathrm{peak}}$ represents the peak supply from the remaining network. Constraint (5) can be simplified as with $\dot{Q}_{net,sep,tot} \cdot \epsilon_{peak} = \dot{Q}_{peak}$ it becomes

$$\dot{Q}_{\mathrm{net,sep,tot}} - \dot{Q}_{peak} \leq \dot{Q}_{\mathrm{source,max}}. \tag{7}$$

Combining Eqs. (6) and (7), the supply constraint is simplified to

$$\dot{Q}_{\mathrm{source}} + P_{\mathrm{el,HP,cen}} + \sum_{c}^{C} P_{\mathrm{el,HP,dec,c}} \leq \dot{Q}_{\mathrm{source,max}}. \tag{8}$$

Constraint (8) does not suppress the installation of HPs as additional power input, as the model can still determine the system for supply, but the network separation is more closely linked to the available heat source capacity, which leads to more realistic DH designs for the separated network.

### 2.3. System components of optimisation model

After presenting the main implementation of community separation within the optimisation model, we describe the DH components of the optimisation model (see Fig. 2). The DH components consumer, HP and HX are based on previous work [29].

#### 2.3.1. Consumer

The consumer model [29], which represents the building and its heating system, prescribes a heat demand with a specific temperature requirement. The heat demand is an input time series, while the required supply temperature of the heating system is determined by a heating curve. This required supply temperature must be met by the substation of the building.

#### 2.3.2. Heat exchanger and heat pump installation

The substation of the building can be represented by two different components. As we deal with existing DH systems, a HX is already part of the substation in each building, i.e. no costs for construction are considered. However, for the design transformation of the separated DH system, we consider the optional HP installation in the buildings' substations to raise the temperature according to local requirements. A design decision is implemented in the consumer model to design either a HX or a HP at the substation [29]. Thus, the optimisation determines the design of the substations based on the required supply temperature of the heating system and the network primary side supply temperature, which is an optimisation variable (see 2.3.3). However, no HP installation is considered for buildings with lower design temperature requirements than the temperature level of the utilised heat source, while considering the estimated heat losses (see 2.3.3). For the HX, a temperature difference between the primary and secondary side of 3 K is assumed. The HX and HP components are described in more detail in [29].

The same principle of design decision between HX and HP [29] is applied for the connection of the new heat source to the separated network, which is represented by the HX/HP component in Fig. 2.

#### 2.3.3. District heating network

The DH network component NET is part of each community (see Fig. 2). The temperature difference between supply and return at the consumers is prescribed by a fixed temperature difference, as it is done in [29]. For the remaining network, the temperature difference is set according to the existing DH system. As the supply temperature in the separated DH network is reduced, the temperature difference also decreases [8]. Therefore, a small temperature difference of 20 K is assumed for the separated DH network, which is within the range of many sustainable DH systems [34]. The supply temperature of the network component NET is an operational variable, i.e. the actual supply temperature level is optimised by the optimisation model depending on the temperature level of the utilised heat source, the temperature requirements of the buildings and the optional installation of HPs. The return temperature of the NET component is determined by the prescribed temperature difference.

No heat losses can be calculated in the network component, as the sub-networks are not yet assigned to the separated or remaining DH system and therefore the operating conditions such as mass flows and temperature levels are not known. However, the temperature losses are estimated before optimisation and taken into account as parameters at the corresponding heat sources, i.e. the losses are considered as fixed temperature differences in the network component NET between heat source and building position depending on the current supply situation. The average temperature losses $\Delta T_{\mathrm{loss}}$ of the network are calculated as a function of the DH temperature $T$ for the supply and return line by

$$\Delta T_{\mathrm{loss}} = \frac{U \cdot 2 \cdot \pi \cdot r \cdot l \cdot (T - T_{\mathrm{ground}})}{2 \cdot \dot{m} \cdot c_p}, \tag{9}$$

with the network length $l$, the mass flow $\dot{m}$, the average heat loss coefficient $U$, the average radius of the pipes $r$, the constant ground temperature $T_{\mathrm{ground}}$=8 °C and the specific heat capacity of water $c_p$ [35]. The temperature losses are calculated once for the supply line and once for the return line, each represented by the DH temperature $T$ in (9). The average heat loss coefficient $U$ and average radius of the pipes $r$ are calculated using available pipe data of the network. The mass flow $\dot{m}$ is calculated with the known temperature difference between supply and return, which is known for the remaining network and prescribed for the separated network. Therefore, the heat losses estimated for the remaining and the separated network depend only on the calculated mass flow of the corresponding network and the temperature level. The DH temperature $T$ of the remaining network is known, while a temperature level of 80 ° C is assumed for the separated network, which marks a conservative estimation. Since a DH simulation is conducted for a feasible DH operation (see 2.5.2), the assumed temperature losses can be checked later on.

#### 2.3.4. Heat sources

The new heat source is modelled with regard to the available temperature level and available amount of heat. The old heat source, representing the conventional heating plant, is modelled with a fixed supply capacity and a supply temperature level that corresponds to the original DH operation. The operating costs and emissions factors are linked to the used fuels. For the new heat source, the investment for the exploitation of the heat source is considered, e.g. for HP installation [36].

#### 2.3.5. Peak load supply for separated district heating system

The remaining DH system forms a backup heat supply for the separated DH system, which can also support the new utilised heat source, e.g. during peak loads. As there is already a hydraulic connection between the remaining and separated DH system, it can be used as a peak load supply option. Thus, a larger network part could be separated from the original network, whose nominal heat demand exceeds the available heat source capacity.

The peak load supply is simplified modelled as an optional heat supply for the separated DH system. The usage of this heat supply is limited to a maximal 20 % of the total heat supply, i.e. $\epsilon_{\text{peak}} = 0.2$, and 10 % of the annual supplied heat to the separated DH system.

*2.3.6. Power supply through the power grid*

The power supply to the optional HPs is modelled by a connection to the public PG, considering the specific emission factor and the associated prices for power consumption.

## 2.4. Objective function

In this study, we consider two different objectives for the optimisation, the total annualised costs (TAC) and the annual $CO_2$ emissions. The TAC is calculated by

$$\text{TAC} = \frac{(1+i)^n \cdot i}{(1+i)^n - 1} \cdot \text{CAPEX} + \text{OPEX}, \tag{10}$$

with a project time span n of 20 a and the interest rate i of 3 %. The capital expenditures (CAPEX) consider the investment for network separation by

$$\text{CAPEX} = I^{\text{pipe}}_{\text{new}} + I^{\text{HP}}_{\text{new}} + I^{\text{HX}}_{\text{new}} + \sum_{c \in C} I^{\text{HP}}_{c}, \tag{11}$$

with the costs for the connection pipe $I^{\text{pipe}}_{\text{new}}$ and the costs for either a central HP $I^{\text{HP}}_{\text{new}}$ or HX $I^{\text{HX}}_{\text{new}}$ construction. The costs for optional HPs at the buildings are considered by $I^{\text{HP}}_{c}$ for each consumer c. The operating expenditures (OPEX) are calculated by

$$\text{OPEX} = \sum_{t \in T} w_t \cdot \left[ p_{\text{el}} \cdot \left( \sum_{c \in C} P^{\text{HP}}_{\text{el},t,c} + P^{\text{HP}}_{\text{el},t,\text{new}} \right) + p_{\text{gas}} \cdot \dot{Q}_{t,\text{old}} + p_{\text{heat,new}} \cdot \dot{Q}_{t,\text{new}} \right] \tag{12}$$

with $p_{\text{el}}$=213.8 EUR/MWh [37] and $p_{\text{gas}}$=70.6 EUR/MWh [38] for the specific constant energy prices for the power consumed from the PG and the gas consumed by the conventional heating plant, i.e. old heat source $\dot{Q}_{t,\text{old}}$. $p_{\text{heat,new}}$ is the price for using the utilised heat source $\dot{Q}_{t,\text{new}}$ according to the type of heat source. $P^{\text{HP}}_{\text{el},t,c}$ and $P^{HP}_{\text{el},t,\text{new}}$ are the power supply to the optional HPs. $w_t$ is the weighting factor of the respective operating point under consideration.

The annual $CO_2$ emissions $m_{CO_2}$ are the second considered objective for network separation and are calculated according to

$$m_{CO_2} = \sum_{t \in T} w_t \cdot \left[ ef_{\text{el}} \cdot \left( \sum_{c \in C} P^{HP}_{\text{el},t,c} + P^{\text{HP}}_{\text{el},t,\text{new}} \right) + ef_{\text{gas}} \cdot \dot{Q}_{t,\text{old}} + ef_{\text{heat,new}} \cdot \dot{Q}_{t,\text{new}} \right], \tag{13}$$

where $ef_{\text{el}}$=366 kg/MWh and $ef_{\text{gas}}$=201 kg/MWh are the emission factors for the gas and power consumption [39], while $ef_{\text{heat,new}}$ are the specific emissions resulting from the usage of the new heat source.

## 2.5. Evaluation of network separation

*2.5.1. Analysing community structure and node positioning*

The optimal solution for community separation is investigated for unfavourable nodes that causes the cutting of loop structures in the separated or the remaining network. This situation is explained with Fig. 3.

Fig. 3 shows an example of a small network area with coloured communities. The critical nodes for separation are marked with dashed cycles. Assume that the edges cut off at the top and bottom of the figure form a loop in the network structure outside of this focus and are part of the remaining network. If one community, red, blue or pink, is selected for separation, the marked nodes are also separated from the network structure, as they are part of the identified community. However, the separation of one of this marked nodes would lead to cutting the loop of the remaining network. However, these type of nodes are not crucial for the separated network as they mark no buildings but network junctions. It is therefore advantageous that such nodes are not separated but stay in the remaining network to maintain the loop. Such a situation could also occur for the separated network if a remaining community has one node in the loop structure identified for separation.

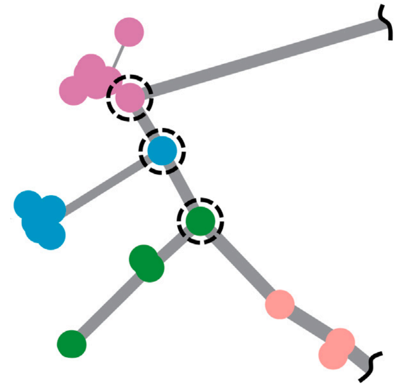


**Fig. 3.** Example for crucial nodes that could lead to cut loops caused by community separation.

To maintain the potential loops in the remaining or separated network, which are only interrupted by a node from the respective other network structure, such nodes are automatically identified and assigned to the respective other network structure. Since no building or important connecting nodes are reassigned, the general structure of the DH separation does not change.

*2.5.2. Simulation of district heating separation*

The DH network component is simplified in the optimisation model, as the temperature losses are estimated and the hydraulic behaviour is not considered. Therefore, the changed DH operation of the resulting DH systems is evaluated in more detail using DH simulations. The DH simulation results can be used to detect bottlenecks or insufficiently supplied buildings resulting from the changed DH operation and to derive necessary measures to avoid these difficulties in the separated DH network but also in the remaining DH network.

For the resulting DH networks, we create simulation models in Modelica. The Modelica models are generated using the open source energy network tool uesgraphs [40], which enables the automated generation of executable Modelica models that are parameterised based on the individual DH network characteristics stored in the graph object in uesgraphs. The simulations are based on the operating conditions obtained by the optimisation and are carried out for one year of operation. We evaluate the DH simulation results as done in [10,26]. We identify arising bottlenecks, where the specific pressure losses in a pipe segment exceed 250 Pa/m, and temporarily insufficient temperature supply to the connected buildings, evaluating the occurring temperature difference at the substation and the time span of insufficient supply.

# 3. Results

The developed optimisation model is applied to the district heating network of Forschungszentrum Jülich, which is visualised in a simplified representation in Fig. 4. This figure also shows two anticipated

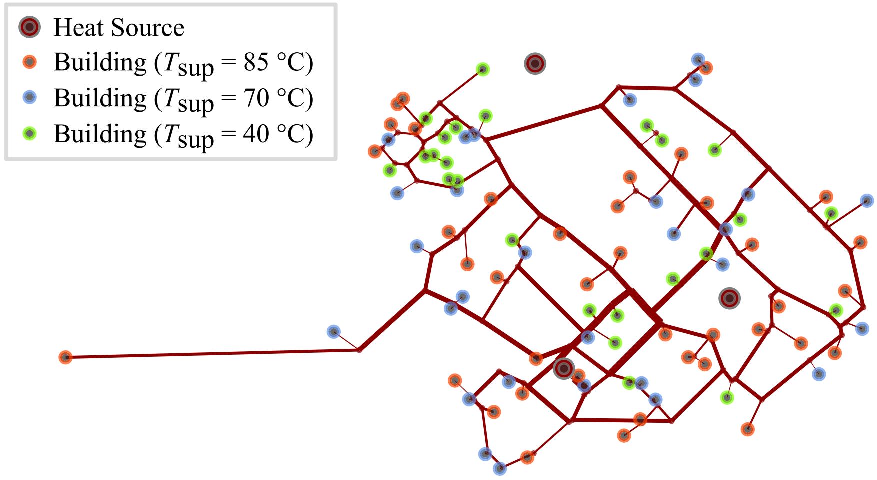



**Fig. 4.** Simplified representation of the existing DH network.

locations for heat sources to be utilised as not yet connected heat source nodes.

The heat demand data for the buildings are available from measurement data for 2017. We estimate the required supply temperatures ($T_{sup}$) of the heating systems based on the known year of construction of the buildings [15,16,41]. For the buildings marked in orange in Fig. 4, the nominal supply temperature at −12 ° C ambient temperature is 85 ° C (year of construction: ≤ 1969), for buildings marked in blue 70 ° C (year of construction: 1970–1999) and for the green buildings 40 ° C (year of construction: ≥ 2000). To manage the network data and simplify the network structure, we use the open source energy network tool uesgraphs [40].

To reduce the computational time of the optimisation [42], we use time aggregation through k-means clustering and cluster the input data into typical operating points that consider the heat demand, the available heat source supply and the ambient temperature. By analysing the data with the elbow method [43], we set the number of clusters to 12. We consider one cluster point at nominal conditions of −12 ° C ambient temperature and maximum heat demand but with zero weight ($w_t$=0) to take care of the required nominal capacities of the optional energy components.

In this work, we investigate the utilisation of waste heat potential of a high-performance computer at a temperature level of 50 ° C. Since this waste heat is provided almost constantly [11], an only slightly fluctuating profile with a minimum waste heat output of 90 % of the nominal capacity is assumed. Since the waste heat is produced anyway, it is assumed that the heat source is freely available and its usage does not lead to any additional $CO_2$ emissions. The OHS that currently supplies the DH system is assumed to be a gas-fired heating plant without cogeneration.

To demonstrate the adaptability of the optimisation model, we investigate two scenarios with different heat source characteristics. The first scenario refers to the waste heat location in the north of the network with a nominal waste heat capacity of 5 MW. The second scenario refers to a waste heat source in the middle of the network (see Fig. 4) and a waste heat capacity of 2.5 MW. For both scenarios, we perform the optimisation once for minimising the TAC and once for minimising the $CO_2$ emissions. The scenarios are summarised in Table 1.

The operating points used in the optimisation model and the associated weights $w_t$ are summarised in Table 2. To illustrate the differences between the operating points, the input data for determining the cluster points are also shown. The available heat from the utilised heat source $\dot{Q}_{source}$ and the total heat demand $\dot{Q}_{net}$ are shown in relative terms. The operating points shown in Table 2 are therefore representative for both scenarios, as the waste heat profile is the same in both scenarios but only the absolute capacity changes.

**Table 1**
Scenarios under investigation for DH network separation with different heat source characteristics.

| Scenario | Capacity | Position | Objectives |
|---|---|---|---|
| 1 | 5.0 MW | North of network | TAC/$CO_2$ |
| 2 | 2.5 MW | Middle of network | TAC/$CO_2$ |

**Table 2**
Clustered operating points used for the optimisation model.

| Operating point | $w_t$ | $T_{amb}$ in °C | $\dot{Q}_{source}/\dot{Q}_{source,max}$ | $\dot{Q}_{net}/\dot{Q}_{net,max}$ |
|---|---|---|---|---|
| 1 | 0.000 | −12.00 | 1.000 | 1.00 |
| 2 | 0.044 | −1.72 | 0.900 | 0.81 |
| 3 | 0.121 | 2.37 | 0.900 | 0.64 |
| 4 | 0.106 | 5.41 | 0.900 | 0.45 |
| 5 | 0.114 | 7.33 | 0.900 | 0.58 |
| 6 | 6.5E−5 | 8.90 | 0.950 | 0.43 |
| 7 | 6.5E−5 | 8.92 | 0.925 | 0.43 |
| 8 | 9.8E−5 | 9.00 | 0.980 | 0.43 |
| 9 | 0.095 | 9.64 | 0.900 | 0.27 |
| 10 | 0.135 | 10.17 | 0.900 | 0.43 |
| 11 | 0.194 | 14.18 | 0.900 | 0.24 |
| 12 | 0.190 | 17.39 | 0.900 | 0.15 |

### *3.1. Community detection in district heating network*

First, the optimal community structure is determined using the Girvan–Newman algorithm. The community structure with the highest modularity in the investigated network structure is shown in Fig. 5.

In total, 14 communities are identified in the network structure. Of the total of $2^{14} - 1$ possible combinations of communities, the check results in 204 realisable combinations.

### *3.2. Optimal district heating separation*

The optimisation problem is solved using Gurobi 10.0.2 [44] on a Windows 10 Enterprise machine with an Intel Core i7-9700 CPU and 32 GB RAM. The problem is solved up to an optimality gap of 1%, which is always achieved within the set time limit of 7200 s.

In the following, the results of DH network separation for both assumed heat source characteristics are presented. For the first scenario, we present the optimisation results and the evaluation of the subsequent DH simulation in detail. For the second scenario, we focus on the optimisation results of DH separation and refer to the appendix for the DH simulation results.

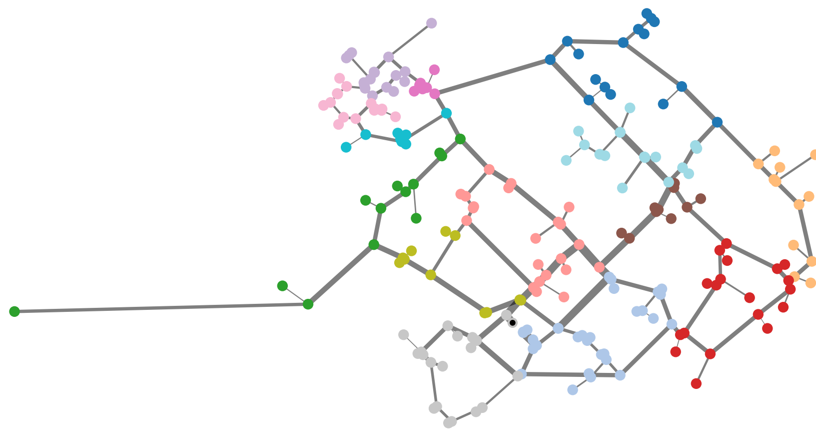


**Fig. 5.** Identified communities in the original network structure.

**Table 3**
DH design of the separated DH networks for an available 5 MW heat source and both considered objectives.

| | Min TAC | Min $CO_2$ |
|---|---|---|
| TAC | 4,325.26 TEUR/a | 4,450.91 TEUR/a |
| $CO_2$ emissions | 11,122.52 $tCO_2$/a | 10,748.01 $tCO_2$/a |
| Communities separated | 3 | 4 |
| Buildings separated | 18 | 23 |
| Nominal central heat supply | 6.07 MW | 4.87 MW |
| Max peak load supply | 1.21 MW | 0.90 MW |
| DH supply temperature | 58-100 °C | 47 °C |
| Central HP capacity | 4.86 MW | 0 MW |
| Number of decentral HPs | 0 | 17 |

### 3.2.1. 5 MW *heat source in the north of the district heating network*

The separated DH networks from the original network structure are shown for minimising the TAC in Fig. 6 and for minimising the $CO_2$ emissions in Fig. 7. The design results of the separated DH systems are summarised in Table 3. For a better representation of the resulting DH networks, the connected building in the west of the network is removed from the figures.

*Objective minimising total annualised costs*

In case of minimising the TAC, three communities in the northern part of the network with 18 connected buildings are separated. A central HP is installed at the utilised heat source to raise the supply temperature to the highest temperature requirement in the network and no decentral HPs are installed at the buildings. Through the peak supply from the remaining network, the realisable heat supply to the separated network is higher than the nominal capacity of the utilised heat source, which is why more buildings can be separated and supplied. The heat supply to the separated DH network, the network supply temperature, the ambient temperature and the temperature level of the heat source concerning the clustered operating points are shown in Fig. 8. The operating points, which are used to optimise the DH network separation (see Table 2), are sorted from left to right with increasing ambient temperatures.

The heat supply of the separated DH system by the central HP $\dot{Q}_{\mathrm{HP,cen}}$ and the remaining DH system $\dot{Q}_{\mathrm{peak}}$ are shown as bar plots, while the network supply temperature $T_{\mathrm{net}}$, the ambient temperature $T_{\mathrm{amb}}$ and the heat source temperature $T_{\mathrm{source}}$ are shown as line profiles. It is mentioned that the heat demand of the DH network can be higher despite higher ambient temperatures, which is due to the non-residential buildings in the investigated DH system that can have a different heat demand at the same ambient temperatures, e.g. due to various weekdays. In addition, operating points 6–8 differ due to the different available heat supply by the utilised heat source, as can be seen in Table 2, which, however, has no influence on the results presented in Fig. 8.

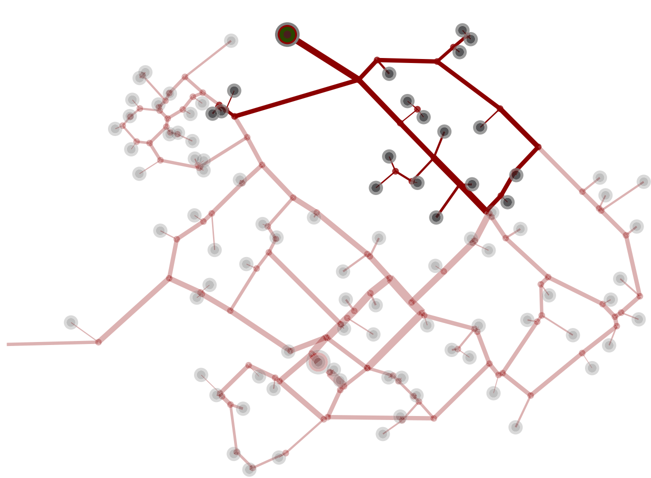


**Fig. 6.** Resulting DH network separation for an available 5 MW heat source for minimising TAC. At the green marked nodes, HPs are installed.

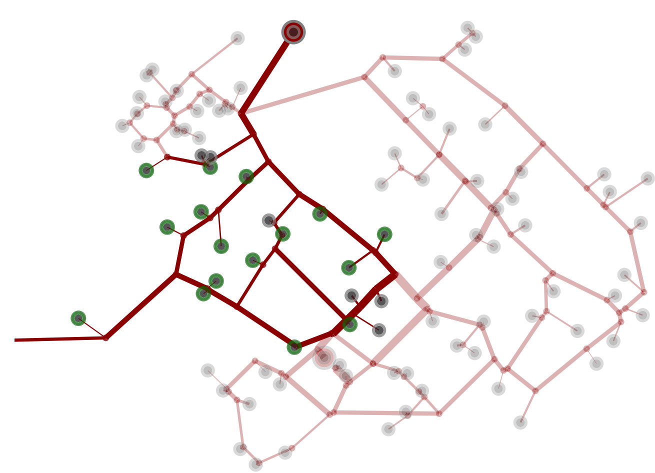


**Fig. 7.** Resulting DH network separation for an available 5 MW heat source for minimising $CO_2$. At the green marked nodes, HPs are installed. At the not shown building in the west, a HP is installed.

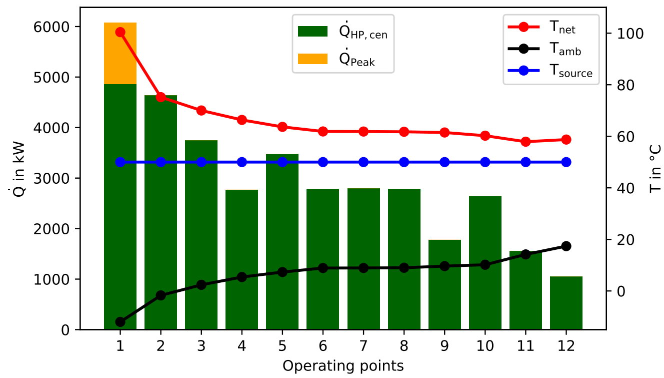



Fig. 8. Heat supply and network temperature level concerning operating points of the separated DH system (Minimising TAC).

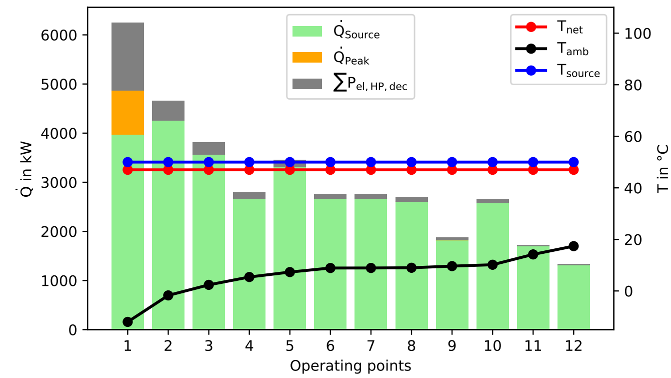



Fig. 9. Heat supply and network temperature level concerning operating points of the separated DH system (Minimising $CO_2$).

The central HP system supplies the DH network using the available waste heat. At low ambient temperatures, the heatcurves in the heating systems of the supplied buildings prescribe a high required supply temperature, which must be met by the central HP. However, the supply temperature at operating point one, the nominal operating point at −12 ° C, is not representative. The supply temperature must be high enough to meet the highest requirements, but even a higher temperature than strictly required might be chosen during optimisation as it has no influence on the objective, since the weight of this operating point is zero ($w_t$=0). In addition, the minimal higher supply temperature at operating point 12 compared to operating point 11 shows that HP operation can still be improved at operating point 12 by lower supply temperatures, which is due to the fact that the optimisation model does only solves up to an optimality gap of 1 %. The peak supply by the remaining network supports the heat supply during the lowest ambient temperature. However, at the other operating points, the heat demand is covered by the HP since its capacity is high enough and the supply is more cost-efficient than with the gas-fired peak supply.

*Objective minimising $CO_2$*

In case of minimising the $CO_2$ emissions, four communities with 23 buildings are separated, which is more than in the case of minimising the TAC. No central HP is built at the heat source, so the heat source supplies the network via a HX. However, several decentral HPs are installed at the buildings to raise the temperature according to the individual supply temperature requirements. The buildings with the lowest supply temperature requirements can be supplied directly via the existing HXs in the substations. The operating points for the separated DH system are shown in Fig. 9. In this case, the operation of the decentral HPs requires external power supply $P_{\mathrm{el,HP,dec}}$, which symbolises an additional energy supply to the DH system (see 2.2.3), and is therefore also shown in Fig. 9.

Most of the supplied heat is provided by the utilised heat source but at low ambient temperatures, the peak supply supports the heat supply to the separated DH network. However, the peak supply is small, as the decentral HPs provide additional power $P_{\mathrm{el,HP,dec}}$ to the supplied buildings by raising the supply temperature. As no central HP is installed in this separated DH design, the network temperature is constant at all operating points.

*Simulation of district heating separation*

The annual dynamic simulation of the two resulting DH networks reveals bottlenecks and buildings with partly insufficient supply. In Fig. 10, the bottlenecks are highlighted by marked edges and the critical buildings by turquoise labels for DH separation concerning minimising the TAC. The pressure losses at the bottlenecks, i.e. the pipes that exceed the threshold value of 250 Pa/m, are also shown in the figure.

The simulation results of the separated network show two bottlenecks and five buildings with partly insufficient supply. As can be seen in Fig. 10(a), the identified bottleneck connecting building D reaches 353 Pa/m during highest mass flows. The second bottleneck connecting building E is more critical, as values of 588 Pa/m are reached here. The critical buildings A, D and E are only insufficiently supplied for a few hours a year with slightly too low supply temperatures at the primary side of the HX. However, at building B and C, the supply temperature gap is larger, so additional measures are required. In the remaining DH network, only one small bottleneck and one critical building are identified. The building is insufficiently supplied for a few hours a year due to unfavourable mass flows. If this DH network separation is realised, these critical areas in the remaining network could be intercepted by small measures. Optional measures to address critical areas in one of the resulting DH networks are discussed later.

For the resulting DH separation concerning minimising the $CO_2$ emissions, the bottlenecks and partly insufficient supplied buildings are shown in Fig. 11.

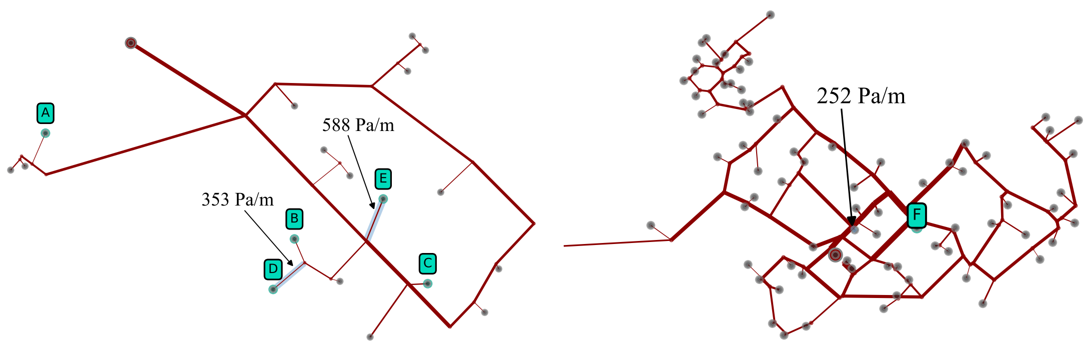
Only two critical buildings are identified in the separated network structure, as decentral HPs increase the supply temperature to the required level at most buildings. The two critical buildings H and G are directly supplied via HXs, but the incoming supply temperatures are too low in some hours of the year since the temperature losses in the network are higher than assumed. In addition, the higher mass flows in the network due to the decreasing temperature difference lead to two minor bottlenecks in the separated network structure.

However, the bottleneck in the remaining DH network is more critical. Due to the separation of main distribution pipes, the entire heat supply in the remaining network must be provided via a small pipe segment in the south of the network. This pipe segment was initially not designed for such high mass flows, which leads to pressure losses of 3442 Pa/m. As this pipe segment is crucial for the network operation, a replacement of this pipe segment is essential to ensure feasible DH operation. However, as the pipe segment is quite short, the cost of replacement is limited.

### 3.2.2. 2.5 MW heat source in the middle of the district heating network

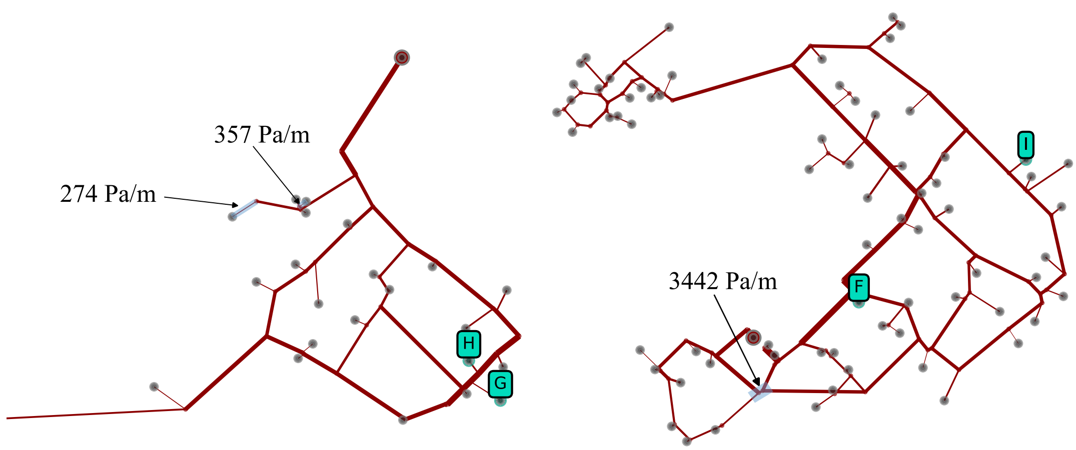
For the second investigated scenario, only the resulting DH separation design is presented here. The detailed operating results from the optimisation (Figs. A.14 and A.15) and the identified bottlenecks and insufficient supplied buildings (Figs. A.16 and A.17) are summarised in Appendix. By changing the nominal capacity and location of the available waste heat source, the optimisation model reveals the separation shown in Fig. 12 for minimising the TAC and in Fig. 13 for minimising the $CO_2$ emissions. The detailed design results of the separated DH networks are summarised in Table 4.

In this scenario, the optimisation reveals the same separation structure for both considered objectives. However, the resulting design for




(a) Separated DH network (b) Remaining DH network

**Fig. 10.** Occurring bottlenecks and partly insufficient supplied buildings due to network separation (5 MW heat source, minimising TAC).




(a) Separated DH network (b) Remaining DH network

**Fig. 11.** Occurring bottlenecks and partly insufficient supplied buildings due to network separation (5 MW heat source, minimising $CO_2$).

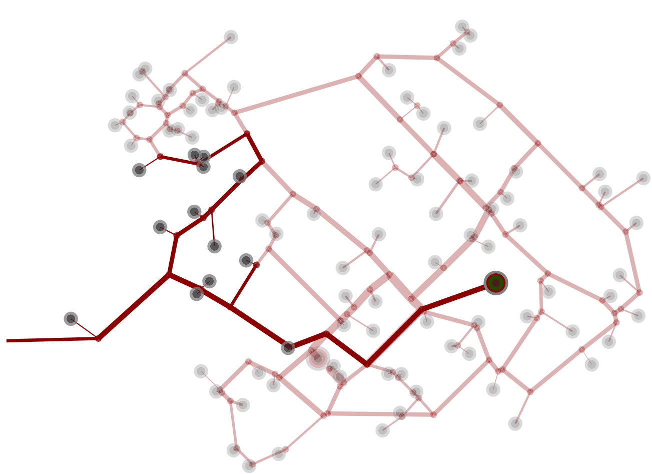


**Fig. 12.** Resulting DH network separation for an available 2.5 MW heat source for minimising TAC. At the green marked nodes, HPs are installed. At the not shown building in the west, no HP is installed.

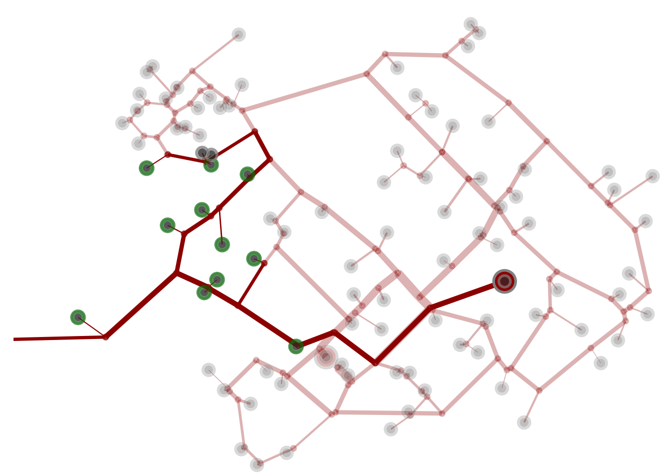


**Fig. 13.** Resulting DH network separation for an available 2.5 MW heat source for minimising $CO_2$. At the green marked nodes, HPs are installed. At the not shown building in the west, a decentral HP is installed.

the separated DH system differs, as only one central HP is installed for minimising the TAC, but decentral HPs are prescribed to minimise the $CO_2$ emissions. The difference in the DH design leads to only minor differences in TAC and $CO_2$ emissions between the two optimisation runs. Nevertheless, the installation of only one central HP minimises the investment, but the individual temperature balance with decentral HPs leads to more efficient HP operation and thus to lower emissions resulting from the power consumption. In addition, the decentral HPs supply additional energy to the heating systems of the buildings due to the required HP operation for temperature raising. This leads to less

**Table 4**
DH design of the separated DH networks for an available 2.5 MW heat source and both considered objectives.

| | Min TAC | Min $CO_2$ |
|---|---|---|
| TAC | 4,778.96 TEUR/a | 4,910.18 TEUR/a |
| $CO_2$ emissions | 12,912.96 $tCO_2$/a | 12,816.53 $tCO_2$/a |
| Communities separated | 3 | 3 |
| Buildings separated | 14 | 14 |
| Nominal central heat supply | 2.91 MW | 1.96 MW |
| Max peak load supply | 0.58 MW | 0.04 MW |
| DH supply temperature | 58-95 °C | 47 °C |
| Central HP capacity | 2.33 MW | 0 MW |
| Number of decentral HPs | 0 | 12 |

required peak supply through the remaining network and thus to an additional reduction in $CO_2$ emissions, as less gas is consumed.

## 4. Discussion

In this section, we first discuss the developed optimisation model and the presented results. Subsequently, we point out some necessary adaptions to the model to apply it to larger network structures.

### *4.1. Optimisation approach and obtained results*

In contrast to the methodology presented in [26], where all possible network separations are simulated and then evaluated, the method in this study is an advanced approach in which the optimal network separation is determined directly based on mathematical optimisation. In addition, the obtained transformation design of the separated DH network is an improvement in this work that is not considered in [26]. However, the developed optimisation model does not yet analyse multi-objective solution for DH separation, e.g. the simultaneous consideration of costs and $CO_2$ emissions, which is therefore currently better possible in [26], as several indicators are calculated that enable the simultaneous evaluation of economic and environmental interests.

The developed optimisation model also considers the situation of the heat source intended for utilisation, since a change in the location and capacity of the heat source leads to different boundary conditions of the optimisation problem and thus to different network separations. In addition, the optimisation objective influences the DH separation and the prescribed design of the separated network, as only one central HP is built for minimising the TAC but individual HP installation at the buildings is preferred to minimise the $CO_2$ emissions.

The subsequent simulation of the two resulting DH systems shows critical supply areas in the networks. However, the additional expenditures resulting from necessary measures are not considered in the economic objective, as they are not known before the optimisation. Although additional expenditure might be necessary for realising the prescribed network separation, the incurring costs for the replacement of a short pipe segment (as revealed in 3.2.2) or the installation of heating rods at partly insufficiently supplied buildings are low compared to the other investment, e.g. the connection pipe or HP installation. Therefore, the unconsidered costs of the subsequently required measures probably do not influence the decision on the optimal network separation.

As explained in 2.3.3, the temperature losses in the network model component cannot be calculated in the optimisation and are therefore estimated beforehand. However, as the DH simulation showed, the temperature losses are partially underestimated. Especially in times with low heat supply, small mass flows in the network lead to high relative heat losses and thus to high temperature drops between supply and consumer. The calculation of the temperature losses assumes a static supply situation with continuous mass flows, which does not correspond to reality, as the changing supply situation in the meshed network structure can lead to very small or even stagnating mass flows. A more conservative estimation of temperature losses in operating points with low heat supply could improve the determination of supply temperature in the optimisation, which would lead to fewer buildings with insufficient temperature supply.

A final point to discuss is the constraint that limits the maximum power supply to the separated DH network to avoid the installation of HPs for the intention of additional energy supply (see 2.2.3). This constraint does not consider the power supply from the HPs that occurs anyway due to the temperature rise. Taking this anyway occurring external power input into account would lead to more available supply capacity for network separation. However, the external power supply is difficult to estimate prior to the optimisation as the DH design is not yet determined, but a factor that orientates on the available heat source capacity could be derived through a sensitive analysis.

### *4.2. Performance and limits of presented optimisation model*

The optimisation model for DH network separation uses simplified modelling approaches to enable the optimisation in a feasible time. Although the DH components are partially simplified, e.g. the pipe network is not modelled in detail, the use of bilinear terms for modelling temperature-dependent energy flows [29] enables a detailed consideration of the temperature requirements of buildings when utilising a low-temperature heat source. In addition, the DH operation is evaluated in much more detail in the subsequent simulation, which addresses the simplified pipe network component in the optimisation model, as pressure and heat losses are modelled in the simulation.

The formulation of the optimisation model shows good performance, as all presented scenarios are optimised to global optimality (1% gap) regardless of the objective function. However, the application of the model to larger DH systems will lead to an increasing number of integer variables, as more design decisions for the supplied buildings have to be considered. This leads to increased model complexity and therefore probably to longer calculation times.

In addition, the number of communities increases with larger network structures, which leads to more possible realisable combinations that need to be checked (see 2.2.2). Since all possible community combinations are currently tested, the check has time complexity $\mathcal{O}(2^n)$, which is not suitable for a rising number of communities. Therefore, an alternative, less complex check for realisable combinations, e.g. by graph search, must be implemented for larger network structures. Alternatively, the total number of communities in the network can be limited, e.g. by clustering building areas to an aggregated consumer node.

## 5. Conclusion

An alternative approach to integrate sustainable heat sources into existing DH systems is to decentralise the network structure into smaller, independent DH systems. Thus, the separated DH network can be transformed much more individually for an efficient heat source utilisation depending on the building characteristics.

In this work, we developed a method to determine the most beneficial DH separation depending on the existing DH network structure. Based on identified communities in the network, an optimisation model determines the optimal network separation and prescribes a DH system design for the separated network structure. Subsequently, the separated and the remaining DH system are simulated for one year of operation to evaluate the sufficient heat supply to all buildings and to identify bottlenecks in detail.

The method is applied to an existing DH system, revealing different network separations and DH system designs for different optimisation objectives. In addition, adapted boundary conditions of the heat source intended for utilisation demonstrate the fast adaptability of the optimisation model to test different heat source potentials and to reveal the resulting network separations. The subsequent network simulations identify critical areas during DH operation from which various measures, e.g. pipe replacement or heating rod installation, can be deduced. This additional analysis is crucial if the proposed separation is implemented in order to ensure reliable heat supply in both network structures.

The presented optimisation model shows good computational performance for the presented use case. However, due to the model formulation and the identification of realisable community combinations, an alternative community check or simplifications of the investigated network structure need to be derived to enable the application of the model to larger DH network structures. Overall, the presented method for separating existing DH systems to utilise available heat sources and gradually transforming the DH system is a promising alternative for decarbonising existing DH infrastructure towards sustainable heat supply systems.

## CRediT authorship contribution statement

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

## 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

### Abbreviations

| | |
|---|---|
| C | All Consumer |
| c | Consumer |
| CAPEX | Capital Expenditures |
| Com | Community |
| DH | District Heating |
| HP | Heat Pump |
| HX | Heat Exchanger |
| NET | Network |
| NHS | New Heat Source to Utilise |
| OHS | Old Heat Source |
| OPEX | Operational Expenditures |
| PG | Power Grid |
| TAC | Total Annualised Costs |

### Symbols

| | |
|---|---|
| $\Delta$ | Difference, - |
| $\epsilon$ | Fraction of Peak Supply, - |
| $\dot{m}$ | Mass Flow, kg/s |
| $\dot{Q}$ | Heat Flow, W |
| $c_p$ | Specific Heat Capacity, J/kgK |
| $ef$ | Emission Factor, kg/Wh |
| $I$ | Investment, EUR |
| $l$ | Length, m |
| $m$ | Mass, kg |
| $P$ | Power Flow, W |
| $p$ | Specific Price, EUR/Wh |
| $r$ | Radius, m |
| $T$ | Temperature, K |
| $\mathcal{T}$ | Time Horizon, s |
| $t$ | Time, s |
| $U$ | Heat Loss Coefficient, W/m$^2$K |
| $w$ | Weighting factor, - |
| $b$ | Design Variable, - |
| $i$ | Index of Summation, - |
| $i$ | Interest Rate, % |
| $j$ | Index of Summation, - |
| $k$ | Index of Summation, - |
| $n$ | Project Time Span, a |
| $n$ | Upper Limit of Summation, - |

### Subscripts

| | |
|---|---|
| amb | Ambient |
| cen | Central |
| combi | Combination |
| dec | Decentral |
| el | Electricity |
| net | Network |
| new | New Heat Source to Utilise |
| old | Old Heat Source |
| peak | Peak Supply Option |
| sep | Separated |
| source | Heat Source |
| sup | Supply |
| tot | Total Heat Supply |

## Appendix

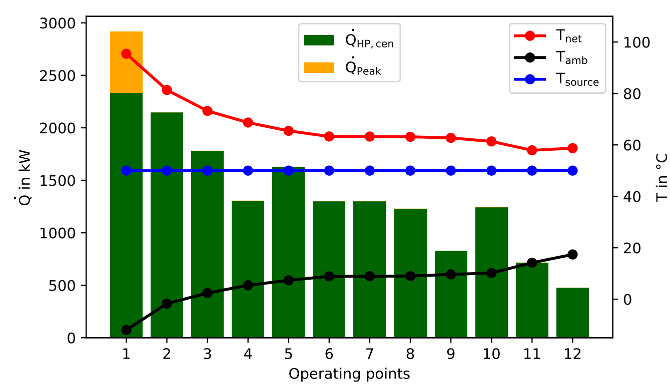



**Fig. A.14.** Heat supply and network temperature level concerning operating points of the separated DH system (2.5 MW heat source, minimising TAC).

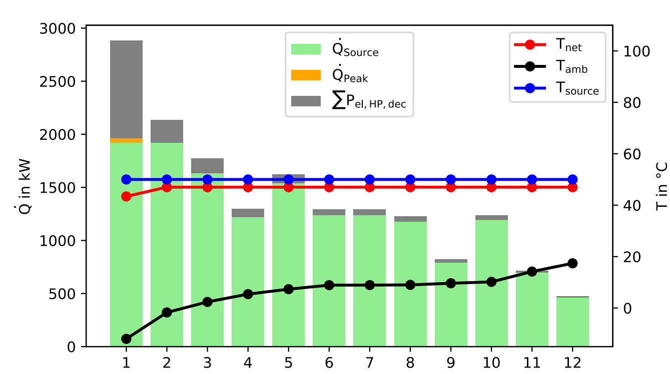
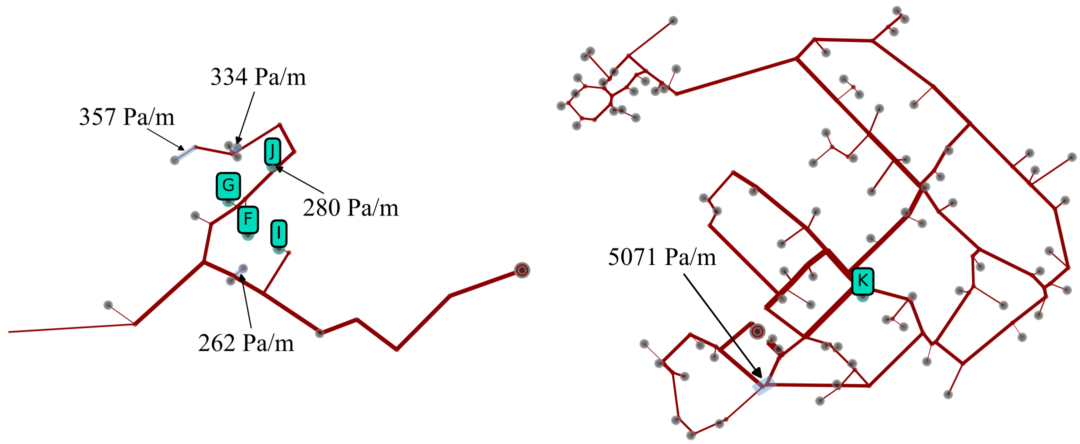
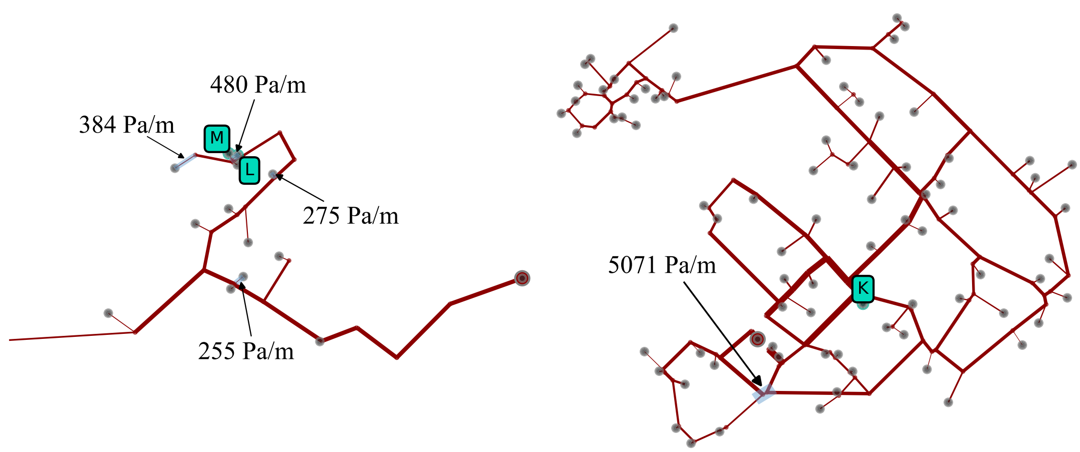



**Fig. A.15.** Heat supply and network temperature level concerning operating points of the separated DH system (2.5 MW heat source, minimising CO2).




(a) Separated DH network (b) Remaining DH network

**Fig. A.16.** Occurring bottlenecks and partly insufficient supplied buildings due to network separation (2.5 MW heat source, minimising TAC). The not shown building in the west is insufficiently supplied.




(a) Separated DH network (b) Remaining DH network

**Fig. A.17.** Occurring bottlenecks and partly insufficient supplied buildings due to network separation (2.5 MW heat source, minimising CO2).

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