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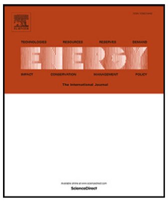

Optimisation of district heating network separation: An extended approach for partial transformation of large-scale network structures[☆]

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ABSTRACT

The decentralisation of existing district heating systems by network separation is a promising approach for district heating transformation. A district heating network is separated into several smaller district heating network structures that can be individually adapted, e.g. in relation to the existing network structure or concerning the properties of the local buildings supplied, such as the temperature requirements of their heating systems.

In this work, an approach for the optimal separation of existing district heating networks is expanded, which enables the decentralisation of a specific district heating system and the partial transformation of the separated network depending on the heat source utilised and the local district heating system conditions. The approach first identifies coherent network areas through community detection and aggregation, then optimises network separation and the installation of heat pumps, and finally evaluates the arising district heating network systems through district heating network simulations. The individual steps of this approach are adapted to be applicable to large district heating network structures, e.g. to handle the great number of separation options.

The approach is applied to two existing district heating systems with over four thousand buildings supplied. Two types of utilised waste heat sources are investigated, a sewage plant with fluctuating temperatures and an electrolyser with a dynamic operation schedule. The results show favourable transformation alternatives for existing district heating networks, as the separated network areas are transformed by reducing supply temperatures depending on the heat source potential utilised and the temperature requirements of the buildings supplied.

1. Introduction

Replacing fossil-based plants in the current energy infrastructure is essential to achieve carbon neutrality in the energy sector. In particular, the heating infrastructure must be transformed into a sustainable energy infrastructure, as it was responsible for almost 38 % of worldwide energy related CO_2 emissions in 2022 [1]. In terms of the heating infrastructure, district heating (DH) systems offer a great potential to reduce CO_2 emissions as sustainable heat sources such as renewables and waste heat sources can be efficiently utilised [2,3]. In general, a DH system comprises the heat sources, the connected buildings and the DH network that distributes the heat. The utilisation of sustainable heat sources is an essential part of the transition or transformation of existing DH systems that aims to improve the efficiency and sustainability of existing heating infrastructure [4,5]. The DH transformation process refers to the adaption of DH system components and the operation, i.e. sustainable heat sources can replace fossil-based heating plants currently in operation [6], the supply temperature can be decreased to reduce the heat losses [7], the pipes of the DH network can be replaced to improve the mass flow conditions and avoid bottlenecks [8] or the connected buildings can be adapted, e.g. by replacing the internal heating system or refurbishing the entire building [9,10].

Sustainable heat source potentials, such as low-temperature waste heat sources or renewables, are often limited in usable heat capacity and are tied to a specific location, i.e. they are decentrally distributed. However, DH networks were mostly organised centrally, e.g. one or a few large heating plants supply the entire DH system. Therefore, a favourable approach for DH transformation, which is in particular suitable for large systems, is the separation of the DH network structure into individual DH networks in order to decentralise large centralised

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Nomenclature

Abbreviations

Com	Community
DH	District Heating
HP	Heat Pump
MIQCP	Mixed Integer Quadratically Constrained Programming
UHS	Utilised Heat Source

Symbols

b	Design Variable, –
G	Aggregated Graph, –
i	Index of Summation, –
k	Index of Summation, –
n	Upper Limit of Summation, –
P	Power Flow, W
$\dot{Q}$	Heat Flow, W
T	Temperature, K
t	Time, s
w	Weighting factor, –
$\mathcal{RC}$	Set of Realisable Combinations, –

Subscripts

amb	Ambient
cen	Central
combi	Combination
net	Network
peak	Peak Supply Option
sep	Separated
rem	Remaining
max	Maximal
min	Minimal

systems into several smaller DH systems. This enables the specific transformation of the separated DH networks depending on local conditions such as the installed pipes, the properties of the supplied buildings and the heat source intended for utilisation [11,12]. Thus, this option represents a partial DH transformation, as the separated network parts are adapted to operate as efficiently as possible with regard to the utilised heat source and the local building properties, while the remaining DH network is not adapted at all. In this work, the approach of DH network separation is applied to large DH network structures, which is described in more detail after the literature review.

1.1. *Literature review*

The literature related to this work first provides a general overview of the transformation of existing DH systems, including their challenges and opportunities. Following, studies focusing on the decentralisation of DH systems are outlined. Finally, an overview of different analytical approaches and tools for analysing DH systems and their transformation is presented.

1.1.1. *Transformation of existing DH systems: challenges and opportunities*

The transformation of existing DH systems is a key element in achieving the decarbonisation of heating supply and increasing overall system efficiency. The main aspects of DH transformation are summarised in [13], including the integration of renewable heat sources, the reduction of DH supply and return temperatures, and the required measures at connected buildings to ensure sufficient heat supply despite lower operating temperatures. A recent study by Lund et al. provides an updated overview of the role of DH in future clean-energy systems and highlights that lowering temperature levels and strengthening sector coupling are essential for achieving carbon neutrality [14]. However, the optimal transformation strategies are also influenced by energy infrastructure in national contexts [5], e.g. in Germany the focus should be on reducing heat demand and improving distribution efficiency, while in France the expansion of power-to-heat technologies is prioritised. The challenges involved in transforming existing DH systems include, for example, the temperature requirements of supplied buildings and the increase in mass flow rates within the pipe network [15]. However, many components of existing DH systems, such as pipe diameters, are often over-dimensioned due to reduced heat demand or anticipated network expansion, which is advantageous for the transformation process [15]. Such over-dimensioned DH components mostly allow for temperature reductions of about 5–10 °C, however, additional measures such as replacing bottleneck pipes or improving fault detection at substations can enable further reductions [7]. An optimisation approach that identifies an optimal combination of transformation measures is presented in [8], including pipe and substation upgrades or the installation of booster pumps, to enable lower supply temperatures. Overall, the aspects of DH transformation are diverse, with a particular focus on temperature reduction and the integration of renewable energy sources. However, most studies concentrate on overall system-level transformation, while the following studies address an alternative approach to DH transformation through decentralisation into DH subnetworks.

1.1.2. *Decentralisation of DH systems*

The decentralisation of DH systems by means of DH subnetworks is increasingly discussed to enhance system flexibility and facilitate the integration of distributed heat sources. Puschnigg et al. introduce the concept of a DH subnetwork, defined as a low-temperature network supplied via the return line of a high-temperature DH system [16], while Volkova et al. interpret the coupling of DH subnetworks more generally as an energy cascade [17]. A techno-economic assessment of integrating DH subnetworks into existing DH systems shows that such subnetworks can reduce return temperatures and thereby increase heat capacity and lowering heat losses [18]. However, setting up subnetworks also leads to greater complexity in system control [16,17]. The separation of existing DH systems into several interconnected subnetworks that are hydraulically separated but thermally linked is proposed by [11], improving overall system flexibility and enabling higher shares of renewable heat. Rämä et al. present the concept of dynamically distributed DH systems, where individual network areas can be partially isolated and operated independently during the heating season [12]. This approach simplifies the transformation of large DH systems by enabling stepwise, area-by-area conversion. Additionally, smaller DH systems can be operated more efficiently through improved storage management and independent temperature control. Capone et al. present a strategy for dynamic supply temperature in DH systems, in which decentralised heat pumps are integrated into a large existing DH network, and part of the network is operated with different supply temperatures [19]. This allows the arising subnetworks to be operated at lower supply temperatures in some cases, while at the same time simplifying the integration of renewable energy. The economic advantages of DH subnetworks are investigated in [20] using a coordinated modelling approach for heat and electric markets. This shows that dynamic supply temperatures in DH subnetworks offer flexibility in heat pump (HP) operation, thus enabling HPs to be operated under favourable market conditions. The presented studies indicate that the decentralisation of DH systems offers promising opportunities for modularisation and acceleration the DH transformation process, while at the same time increasing the share of sustainable heat sources. Following, approaches and tools for investigating the DH transformation process are summarised, with an additional focus on approaches for identifying subnetwork structures in DH networks.

1.1.3. Tools and approaches for investigating DH transformation

A wide range of analytical tools and modelling approaches has been developed to investigate DH systems and their transformation processes. Kuntuarova et al. compare existing DH simulation tools with respect to their modelling approaches (steady-state, quasi-dynamic, or dynamic thermo-hydraulic) together with their application scope and functional capabilities [21]. A dynamic DH network simulation approach is used in [22] to analyse possible transformation pathways for a DH system in Germany. Using mathematical optimisation models for analysing DH systems is an efficient approach to identify optimal design and operation for planning new, but also to transform existing DH systems [23,24]. As the utilisation of renewables is crucial in DH transformation, Wang et al. provide an optimisation approach that reveals optimal integration of renewable energy sources into existing DH systems while minimising pumping energy [25]. In addition, an optimisation model developed by [26] enables matching spatially distributed energy sources with heating and cooling demands in DH and cooling networks. Regarding the DH transformation process, Vannahme et al. propose an approach to evaluate different optimisation measures for existing DH systems and derive a guideline for DH operators to identify suitable measures for their system categories [27]. For DH network expansions, [28] developed an optimisation model that optimally designs the pipe dimensions required, considering pressure drops, flow velocities and heat losses. Focusing on the approach of decentralisation and DH subnetworks discussed before, several studies address methods for aggregation and clustering in the context of DH. For example, a building-clustering model is proposed in [29], which is based on consumption and spatial location, applicable for assessing waste-heat potential and DH network planning. Felsmann et al. identify clusters of consumers within a DH network based on geographical location and required supply temperature, supporting the integration of low-temperature heat sources [30]. Alternatively, the model developed by [31] is used to aggregate buildings into single consumer nodes to estimate storage and demand-side management potential. Overall, existing studies provide extensive insights into DH transformation strategies, decentralisation concepts, and analytical tools, such as optimisation and clustering approaches for analysing DH systems and their transformation. However, most studies treat the tools for analysing DH transformation and decentralisation separately, while the interaction between both aspects remains insufficiently addressed.

1.2. Research gap and contribution

As outlined before, an approach to facilitate the DH transformation process and the utilisation of sustainable heat sources in existing DH systems is the decentralisation of DH networks through separation into DH subnetworks. Depending on the location and capacity of an available heat source, a suitable area of the existing network structure can be separated from the main network so that two disconnected subnetworks are created, one supplied by the utilised heat source and the other continues to be supplied by the original heating plants. This mitigates or even eliminates the hydraulic operational difficulties associated with integrating the heat source into the entire DH network, as both resulting DH networks are controlled independently. Furthermore, the integration of low-temperature heat sources is facilitated by network separation, as only the separated network and thus a limited number of buildings need to be examined for possible DH temperature reductions and adapted if necessary. Therefore, the decentralisation of large existing DH systems by network separation is a promising transformation approach, as it allows for specific DH system adaptions depending on the local conditions, thus minimising the overall effort and barriers compared to adapting the entire large DH system at once.

In this work, a previously presented approach of separating existing DH networks is expanded. In [32], a comprehensive modelling approach is introduced that enables the optimisation and evaluation of DH network separation with the aim to utilise an available, as yet unused sustainable heat source. The modelling approach is applied to a fairly small DH system with fewer than a hundred buildings supplied in [32]. Since DH transformation through DH network separation is particularly interesting for large DH systems with thousands of connected buildings, the approach is expanded and applied to large DH networks in this work. Several steps of the approach are adapted to cope with the increasing network size and number of buildings supplied in such large DH systems, i.e. to handle the increasing number of separation options and the increasing complexity in the network structure. A graph search algorithm is used to determine efficiently contiguous network areas in the analysed DH network structure that are suitable for separation. In addition, an alternative simulation approach is applied to enable the evaluation of the arising large DH network structures. Two DH systems with several thousand supplied buildings are analysed for possible DH network separation, whereby heat sources with fluctuating temperatures and heat profiles are examined.

This work is structured as follows: The main approach of DH network separation analysis and the extensions required to be applicable to large DH systems are described in Section 2. The analysed DH systems are introduced in Section 3. Subsequently, DH network separation results are presented in Section 4. In Section 5, the expanded approach is discussed, while Section 6 concludes the work.

2. District heating network separation

The basic approach of DH network separation is originally developed and applied to a small DH network that supplies less than a hundred buildings in [32]. To expand its applicability to DH networks with different structures and sizes, the approach is further developed in this work. However, for reasons of continuity, the approach is presented as a whole in a summarised way, and adaptions compared to [32] are mentioned at the appropriate place in the text.

The approach of DH network separation consists of three steps, which are illustrated with a simple DH network structure in Fig. 1. First, coherent areas, i.e. contiguous network parts, within the existing DH network structure are identified by a community detection algorithm and aggregated to realisable combinations of communities that are options for separation (see Section 2.1). Second, the community combinations are used in the optimisation model, which determines optimal network separation and installation of HPs with regard to an economic objective function (see Section 2.2). Third, the arising DH networks, the separated and the remaining DH network, are evaluated using simulation models to identify critical areas in the DH networks (see Section 2.3), such as bottlenecks (pipes with pressure losses >250 Pa/m) or insufficiently supplied buildings (DH supply temperature T_{DH} lower than temperature requirements of buildings T_{req}).

2.1. Community detection

2.1.1. Communities in a network structure

The first step is to identify coherent areas in the existing DH network structure that are advantageous for separation. To do so, a community detection algorithm is used that identifies coherent group of nodes in a graph representation of the analysed network structure, so-called communities, based on the local node density or the number of connecting edges between a set of nodes [33]. As in previous work [32], the Girvan-Newman algorithm is used to identify communities in the DH network structure since it takes into account the connecting edges between the nodes when identifying communities [34]. The n_{Com} identified communities are used in the following to create discrete options for DH network separation. Separated communities form the separated DH network supplied by a utilised heat source, while the other communities constitute the remaining DH network.

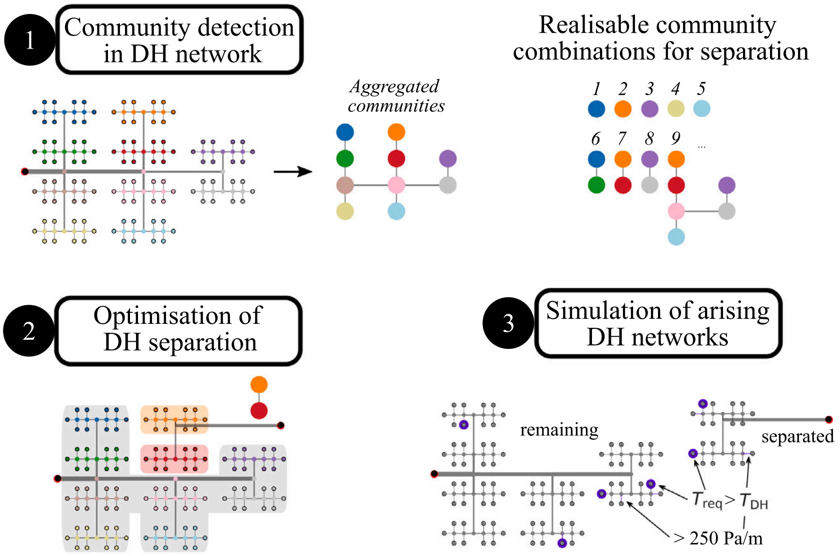

Fig. 1. The three steps of DH network separation illustrated with a simple DH network structure. The steps are described in detail in Sections 2.1, 2.2 and 2.3.

2.1.2. Realisable combination of communities

Both single communities and combinations of communities are potential options for network separation, resulting in $2^{n_{\text{Com}}} - 1$ possible community combinations. Since coherent network areas should be separated, non-contiguous community combinations are not a valid option for separation. Furthermore, the separation of communities that would lead to more resulting network parts than available heat sources is not realisable, i.e. each arising DH network should be supplied either by the newly utilised heat source or by an existing heating plant. Therefore, not every community combination from all $2^{n_{\text{Com}}} - 1$ possibilities is realisable for separation.

The community combinations realisable for separation are identified by: (i) checking the connectivity of a community combination and (ii) checking the sufficient heat supply if the corresponding community combination would form a DH network separation. If a community combination fulfils these conditions, it is referred to as a realisable community combination and added to a set of realisable combinations $\mathcal{RC}$, which is important for the optimisation model described later.

(i) Contiguous community combinations. To identify connected communities for network separation, i.e. contiguous community combinations, the community structure of the DH network is represented as an aggregated graph G in which each node represents a community, while the contiguous relationships between communities are represented by edges between the corresponding nodes in G (see also step 1 in Fig. 1). Checking all $2^{n_{\text{Com}}} - 1$ community combinations in the original network structure, i.e. node combinations in the graph G, for connectivity is $\mathcal{O}(2^n)$ expensive. This check of all possible combinations for connectivity is applied in previous work [32] for a small DH network with 14 identified communities. However, as the number of communities increases with the network size, the number of possible community combinations increases exponentially, which is computationally expensive as memory usage and computational time increase significantly.

In this work, a less computationally expensive approach is implemented that allows the investigation of large network structures with an increasing number of communities n_{Com}. As an alternative to checking all $2^{n_{\text{Com}}} - 1$ combinations for connectivity, the given connection structure within G is used as a criterion for a search algorithm. The identification of contiguous node combinations can be interpreted as finding induced subgraphs of G, as an induced subgraph contains all edges connecting a selected set of nodes of the original graph [35]. It follows that by finding all induced subgraphs of the aggregated graph G, all contiguous node combinations within the graph are revealed.

An approach for finding all induced subgraphs, referred to in the following again as contiguous node combinations, is presented by [36]. The proposed approach is a search algorithm that searches a recursion tree of a connected graph for contiguous nodes. From a starting node i, all contiguous nodes are visited, which in turn visit the contiguous nodes. Thus, all contiguous node combinations for the starting node i are found. By repeating this search strategy, using each node of the graph as a starting node i, all possible contiguous node combinations in the graph are found.

Although the algorithm presented by [36] has linear time complexity $\mathcal{O}(n)$, and is therefore much faster than the entire check of all $2^{n_{\text{Com}}} - 1$ possible combinations, it also reaches computational limits for large networks since the total number of contiguous node combinations increases significantly with each additional node in G. Therefore, the nodes considered in G, i.e. the communities of the original DH network, must be restricted to limit the total number of contiguous node combinations for large networks.

First, the considered nodes are restricted by considering the heat demand. Each node in G is weighted with the summed nominal heat demand of all buildings present in the respective community of the DH network. Thus, a node combination in G can be evaluated in terms of heat demand. If the heat demand of a contiguous node combination exceeds the available heat capacity for DH network separation, the search for larger node combinations is terminated since they cannot be supplied anyway. In this way, the size of contiguous node combinations is limited and thus the total number of possibilities for node combinations in G. The available heat capacity for DH network separation is represented by the nominal capacity of the utilised heat source and an optional peak supply by the remaining DH network (see Section 2.2.3).

Second, the total number of contiguous node combinations in G is reduced by neglecting communities that are far from the location of the heat source to be utilised, as they are less favourable for separation. The shortest connection path from each community to the heat source is calculated along the network structure to obtain a distance for each community. Communities with the largest path lengths are unfavourable for separation and the representative nodes of these communities in G are neglected in the search algorithm to limit the total number of node combinations. The required neglecting rate of communities to handle the number of continuous node combinations in G depends on the network size and the available heat capacity of the utilised heat source, as this already limits the size and therefore the total number of combinations. Different DH network sizes with up to 83 communities and different available heat source capacities are tested to determine the required proportions of neglected communities. This evaluation revealed that 20 % of the most distant communities should be neglected if the heat source capacity is in the range of 20 % of the nominal DH network heat demand, while for higher heat source capacities, up to 50 % of the most distant communities must be neglected to handle the number of node combinations with average available computational resources.

(ii) Sufficient heat supply to community combination. Finally, all identified contiguous community combinations must be checked for a realisable separation into networks that can be supplied by the newly utilised heat source and the existing heating plants. In previous work [32], the DH system under investigation was supplied by one existing heating plant. It was therefore sufficient to check that only contiguous communities are separated that do not lead to a separation into more than two networks. However, in a DH system with several existing heating plants and one heat source to be utilised, the separation into more than two networks could be realisable if all arising DH networks are still connected to a heat source with sufficient heat capacity. Therefore, each contiguous community combination found in the previous step is checked for this aspect. In other words, assuming that the specific community combination is separated from the original DH network, it is checked whether the arising DH networks are still connected to a heat source whose heat capacity could cover the nominal heat demand of all existing buildings in the respective network.

2.2. Optimisation of network separation

The second step of DH network separation (see Fig. 1) is an optimisation model that determines optimal DH network separation and HP installation depending on the utilised heat source. The components of the DH network are modelled with bilinear terms to consider temperature-dependent energy flows. In this way, the temperature requirements of the buildings supplied can be taken into account if a heat source with a limited temperature level is utilised. The optimisation problem is thus a Mixed Integer Quadratically Constrained Programming (MIQCP) formulation, which is implemented as two-stage optimisation in the optimisation framework COMANDO [37]. The optimisation is solved regarding the objective function of total annualised costs using the Gurobi solver [38]. The total annualised costs comprise the capital expenditures, i.e. costs for the heat source utilisation, the connection pipe and the HP installation, and the operating expenditures, i.e. costs for the operation of the existing heating plants, the newly utilised heat source and the HPs, which is described in more detail in [32]. Typical operating points are considered in the optimisation, which are generated by clustering according to the available heat and temperature level of the heat source utilised, the heat demand of the original DH network and the ambient temperature (see also Appendix A). The operating points are weighted (w_t) according to the cluster size. In addition, a design operating point with a weight of zero ($w_t = 0$) at an ambient temperature of −12 °C and maximum heat demand is considered for designing the capacity of the components [32,37]. The main aspects of the optimisation model are highlighted below. For a more detailed description of the model, e.g. with regard to the modelled DH components or the assumed costs, it is referred to [32].

2.2.1. Separate contiguous network areas

Each community in the DH network is modelled as a subnetwork that has two connection decisions represented by design variables b. A community can be either connected to the newly utilised heat source, i.e. be allocated to the separated DH network (b_{sep}), or can be connected to the existing heating plants, i.e. be allocated to the remaining DH network (b_{rem}). A community is connected if $b = 1$, while the respective other connection is $b = 0$ (see constraint (1)). Thus, only one DH network allocation is realised for each community.

$$b_{\text{rem},i} + b_{\text{sep},i} \leq 1 \quad \forall i \in \{1, \dots, n_{\text{Com}}\} \tag{1}$$

To guarantee that just communities forming a realisable community combination are separated, which are grouped into the set of realisable community combinations $\mathcal{RC}$ (see Section 2.1.2), additional constraints are implemented in the optimisation model. For each realisable combination k in $\mathcal{RC}$, constraint (2) is applied, representing the design variable $b_{\text{combi},k}$ as the separation decision of the corresponding realisable community combination k and the design variables of all community connection decisions b_{rem} and b_{sep} in accordance with the realisable combination k.

$$\sum_{i=1}^{n_{\text{Com}}} b_{\text{rem/sep},i} \geq b_{\text{combi},k} \cdot n_{\text{Com}} \quad \forall k \in \mathcal{RC} \tag{2}$$
$$\text{with} \quad b_{\text{rem/sep},i} = b_{\text{rem},i} \vee b_{\text{sep},i} \quad \forall i \in \{1, \dots, n_{\text{Com}}\}$$

$b_{\text{rem/sep},i}$ describes the connection variable b_{sep} or b_{rem} that belongs to the corresponding community in the realisable community combination k to specify the allocation to the separated or the remaining network for each community in the DH network. For communities that belong to the realisable community combination, b_{sep} is added to the sum, while for all other communities b_{rem} is added.

The variable for separating the corresponding realisable community combination $b_{\text{combi},k}$ is multiplied by the total number of communities n_{Com} (see constraint (2)). In this way, the realisable combination k is chosen by the optimisation when $b_{\text{combi},k} = 1$, as this is the only condition under which constraint (2) is satisfied, i.e. the corresponding communities of combination k are allocated to the separated DH network and the other communities to the remaining DH network. As just one realisable community combination can be chosen for network separation, the sum of all $b_{\text{combi},k}$ across all realisable community combinations $n_{\text{combi}} = \#\mathcal{RC}$ must be equal to one

$$\sum_{k=1}^{n_{\text{combi}}} b_{\text{combi},k} = 1. \tag{3}$$

The connection pipe and the associated construction costs for connecting the utilised heat source to the separated DH network are taken into account. For each realisable community combination k, the shortest path between the corresponding community combination and the heat source is calculated and the associated costs for a pipe with the required pipe diameter are linked to the decision variable $b_{\text{combi},k}$. In this way, the location of the heat source utilised is taken into account since different construction costs arise for DH separation depending on the selected community combination.

2.2.2. Installation of heat pumps

HPs may be required in the separated DH network to increase the supply temperature either decentrally at the supplied buildings or centrally for the entire separated DH network at the utilised heat source. Therefore, a design decision is considered for each building, either to use the existing heat exchanger without associated construction costs, since the connection to the DH network is already in place, or to install a HP at the substation of the building, which involves construction costs. However, at the utilised heat source, construction costs for either a heat exchanger or a HP are always considered. The power supply costs for operating the HPs are taken into account in the optimisation model.

2.2.3. Peak supply through remaining district heating network

After separation, the separated and remaining DH networks operate independently of each other. However, the existing pipe that previously connected the arising networks, which is no longer used in normal operation, can be used as an optional peak load supply. This approach allows a larger network area, whose nominal heat demand exceeds the utilised heat source capacity, to be separated from the original network, allowing a higher overall heat utilisation rate of the heat source. For this reason, a peak load supply option from the remaining network with predefined maximum supply proportions is implemented in the optimisation model. The usage of the peak load supply is restricted to 10 % of the annual heat energy and 20 % of the total heat supply to the separated DH network [32]. The peak supply option is implemented in a simplified form in the optimisation model, as it is assumed that the remaining DH network supplies the separated DH network at the same operating conditions. In reality, measures are required to achieve the same supply temperature level from the remaining to the separated DH network, but these are neglected in the optimisation model.

2.3. *Simulation of arising district heating systems*

In the third step of DH network separation (see Fig. 1), the arising DH networks are simulated to evaluate a feasible DH network operation of the separated, but also of the remaining DH network. In previous work [32], the modelling language Modelica is used to create DH simulation models. The applicability of Modelica models for simulating DH networks is however limited to comparably small DH networks, as a complex dynamic simulation approach is used. Since large DH networks are analysed in this work, the pipe network simulation tool *pandapipes* [39] is used, which uses a static simulation approach and allows the analysis of large network structures. The *pandapipes* simulation models for all arising DH networks are created automatically based on the network separation results obtained from the optimisation model.

The simulation results are analysed in terms of the hydraulic and thermal conditions in the arising DH networks to identify possible critical areas for DH operation, as also done in [32]. The pressure losses in the pipe networks are evaluated and occurring bottlenecks with specific pressure losses of more than 250 Pa/m are identified [40]. The thermal DH network conditions are also analysed, as buildings in the DH network with temporarily insufficient temperature supply are detected.

3. Analysed district heating systems

This section presents the two DH systems and the heat sources to be utilised in the context of DH network separation. Since detailed data is not available for large DH systems, two existing DH systems are modelled using the workflow described in [41]. In this workflow, open-source data is collected and aggregated into a comprehensive DH model that can be used for analysing DH transformation measures. Although the DH models are not yet validated with the real DH systems, these models are plausible for the investigation of large-scale network structures and can be used for analysing DH network separation since the most important information about the network structure and local buildings supplied is available, which have the greatest influence on decisions regarding network separation.

3.1. *District heating system of Bottrop*

The first DH system analysed is the DH system of Bottrop, Germany, which supplies around 4400 buildings [41]. The network structure is characterised by many tree-shaped elements, while one central heating plant supplies the DH system. The DH network and the location of the heat source to be utilised are shown in Fig. 2.

For the DH separation of the Bottrop DH system, the waste heat utilisation from an existing sewage water plant is considered. In the southeast of the city of Bottrop, a sewage water plant processes a continuous wastewater mass flow of 8500 kg/s [42]. With a possible temperature extraction of 4 °C [43], the sewage plant in Bottrop offers a low-temperature waste heat potential of over 140 MW. The fluctuating temperature of the wastewater is assumed on the basis of measurement data from a similar sewage plant [44] and varies between 10 °C and 23 °C (see Fig. C.14). In addition, it is assumed that the waste heat can be utilised free of charge, which is of course a special assumption from an economic point of view.

The DH network separation is analysed for different assumed waste heat capacities that can be used at the sewage water plant in Bottrop to demonstrate the effect on the optimal solutions. Therefore, the presented approach of DH network separation is applied for waste heat capacities of 5 MW and 20 MW. The operating points used as input for the optimisation model are shown in Table A.4.

3.2. *District heating system of Essen*

The second DH system to be analysed is the DH system of Essen, Germany, which has a much higher meshed network structure and four heating plants in operation [41]. With around 8000 buildings supplied, the Essen DH system is much larger than the one in Bottrop. For that reason, the building nodes in the graph representation are clustered to 4000 aggregated consumer nodes [41] to limit the size of the DH model to a reasonable level and thus still be able to apply the optimisation model for DH network separation. The DH network and the location of the heat source utilised are shown in Fig. 3.

It is planned to install an electrolyser with an electrical power input of 10 MW near the DH system [45]. Since about a third of the power input is converted to waste heat, the electrolyser is a promising waste heat source for utilisation in the DH network separation analysis. In order to analyse a large amount of waste heat, it is assumed that the electrolyser capacity on the planned construction site will be expanded in the future to a nominal electrical capacity of 50 MW. In addition,

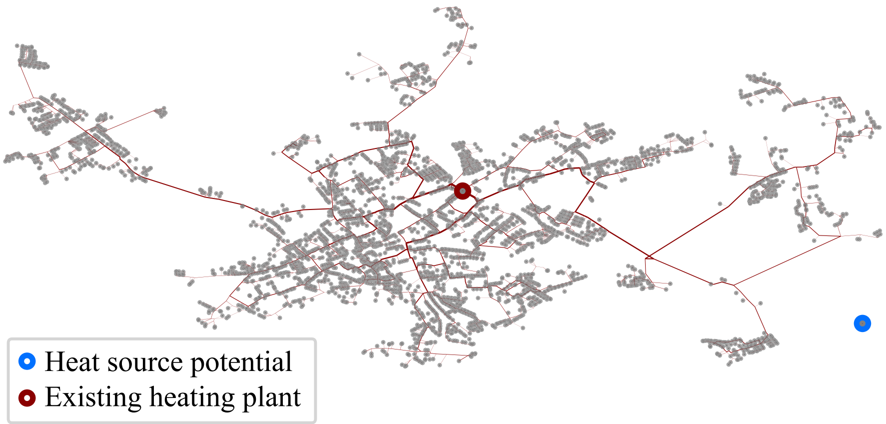

Fig. 2. Original Bottrop DH network structure, showing also the existing heating plant and the heat source to be utilised.

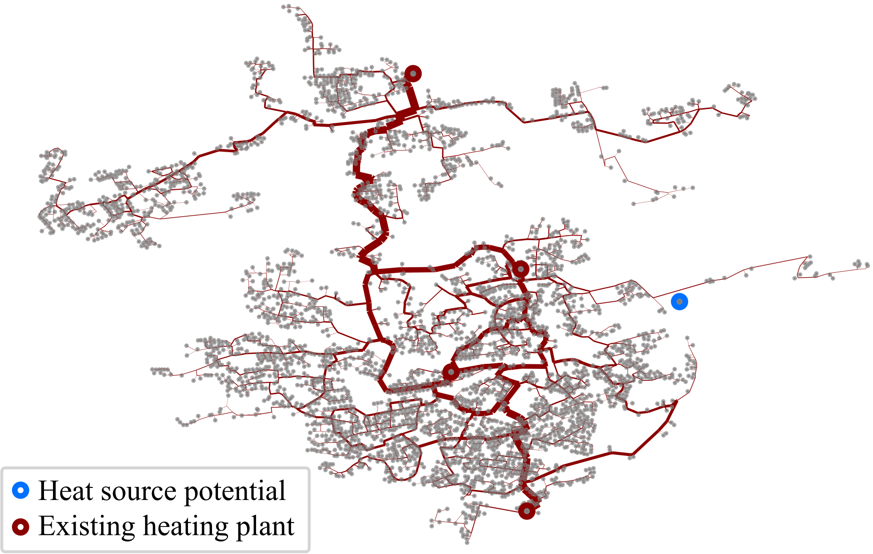

Fig. 3. Original Essen DH network structure, showing also the existing heating plants and the heat source to be utilised. The edge thickness indicates the relative diameters of the network pipes.

Table 1
Assumed heating curves for the supplied buildings, i.e. maximal temperature $T_{\max}$ at $-12\,°\mathrm{C}$ and minimal temperature $T_{\min}$ at 15 °C.

	$T_{\max}$ in °C	$T_{\min}$ in °C
≤1969	85	50
1970–1999	70	40
≥2000	40	30

it is again assumed that the waste heat generated during operation will be made available free of charge by the electrolyser operator. A utilisable waste heat potential of 35 % of the input power [46], corresponding to 17.5 MW of waste heat, at a temperature level of 70 °C [46] is defined. In addition, it is assumed that the electrolyser under consideration is operated according to the electricity price [47], i.e. at low electricity prices the electrolyser is operated at full load, whereas at high prices it is operated at a minimum part load of 50 %. The resulting fluctuating waste heat profile is shown in Fig. D.16. The operating points considered in the optimisation model are listed in Table A.5.

3.3. Temperature requirements of supplied buildings

As the supply temperature of the separated DH network is optimised as part of the DH transformation process, it is important to consider the required temperatures of the heating systems of the supplied buildings. The temperature requirements are estimated based on the year of construction of the corresponding building, taking into account three different construction periods. The required supply temperatures of the heating systems at nominal conditions are estimated on the basis of several review articles [9,48,49], supplemented by an outdoor temperature-controlled heating curve for each building. The construction periods and the associated heating curves are summarised in Table 1. The spatial distribution of the buildings with regard to the temperature requirements of their heating systems is shown in the appendix, in Fig. C.15 for the Bottrop DH network and in Fig. D.17 for the Essen DH network.

4. Results of district heating network separation

The two presented DH systems are used to analyse the DH network separation using the extended approach of Section 2. The size of the resulting optimisation problem for these analyses and the settings for solving these problems can be found in Appendix B. The results of the Bottrop DH network separation focus on the separation decision, while the Essen DH network separation highlights the evaluation of the arising DH networks.

Table 2
DH design of the separated DH networks for two different assumed waste heat capacities at the sewage water plant. The costs are stated in thousands of euros (TEUR).

	5 MW waste heat	20 MW waste heat
Total annualised costs	16,291 TEUR/a	16,283 TEUR/a
IDs of communities separated	10, 11	10, 11, 12, 16, 18, 19, 26, 31, 34, 44, 56, 67, 76, 77, 79
No. of buildings separated	117	798
No. of decentral HPs	0	0
Nominal central heat supply	1.70 MW	14.67 MW
Central HP capacity	1.36 MW	11.74 MW
Decentral HP capacity	0 MW	0 MW
Max. peak load supply	0.34 MW	2.94 MW
DH supply temperature	88 °C	88 °C

4.1. Separation of Bottrop DH network utilising sewage water

The identified community structure in the DH network of Bottrop is shown in Fig. 4. These communities are used in the optimisation model to determine the separation of the DH network. The general design results of the separated DH networks for both waste heat source capacities of 5 MW and 20 MW are summarised in Table 2.

A DH network area that comprises community 10 and 11 is separated in the case of a 5 MW waste heat source, while 15 communities are separated in the case of a 20 MW waste heat source. In both cases, the separated DH network is transformed by installing a central HP to increase the temperature of the utilised waste heat to the required DH supply temperature, so that all buildings connected to the separated network can be sufficiently supplied. The difference between the installed HP capacity (1.36 MW and 11.74 MW) and the nominal DH supply (1.70 MW and 14.67 MW) is covered by the peak load supply from the remaining DH network. The decision of the optimisation model to install a central HP instead of decentral HPs at the buildings is due to the lower investment for a central HP compared

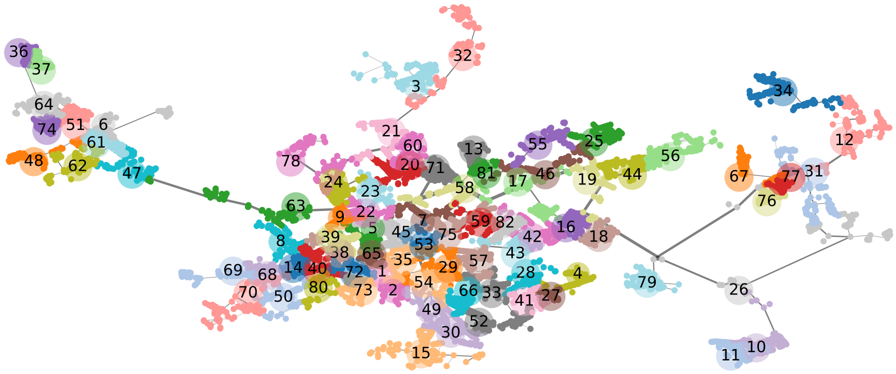

Fig. 4. Community structure for the Bottrop DH network detected by the Girvan-Newman algorithm.

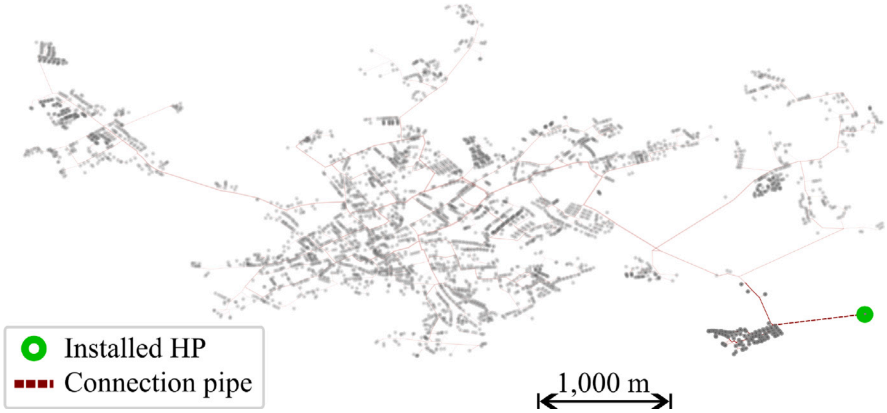

Fig. 5. Bottrop DH network separation utilising a 5 MW heat source.

to installing several HPs at critical buildings, in particular as each building would need a HP due to the low available temperature level at the waste heat source. However, decentral HPs allow an improved operation efficiency, which is why this installation scheme is favoured for a changed optimisation objective that focuses on minimised CO_2 emissions, which is illustrated and described in [32]. The following subsections describe the results in more detail regarding the separation decision, the DH supply temperature or the peak supply.

4.1.1. 5 MW waste heat potential

The DH network separated from the original network structure for a 5 MW utilised heat source is shown in Fig. 5. The separated DH network is highlighted, while the remaining network is faded.

The separated DH network has a nominal heat supply of 1.7 MW, which is low compared to the available heat source capacity of 5 MW. However, the comparably low heat utilisation rate can be explained by considering the community structure of the Bottrop DH network shown in Fig. 4. In the eastern part of the DH network, where the waste heat source is located, not many favourable realisable community combinations for network separation are identified, i.e. only small community combinations realisable for separation are found. As can be seen in Fig. 4, community 26 is centrally located in the eastern network area and therefore limits the possible community combinations for separation, i.e. if community 26 is separated, many neighbouring communities also need to be separated. In other words, the selected DH network area for separation, which includes community 10 and 11 (see Fig. 5), cannot be extended by the neighbouring community 26, as then the community 79 and communities 12/31/34/66/76/77 would no longer be connected to any supplying heat source. Therefore, there is no alternative realisable community combination near the utilised heat source that would allow a higher heat utilisation rate, as community 26 limits the extensions of the community combinations 10/11 or 79.

Nevertheless, other realisable community combinations would lead to a higher waste heat utilisation rate due to higher heat demands, e.g. community combination 12/31/34 with a nominal heat demand of 4.6 MW or the larger community combination 12/31/34/66/76/77 with a heat demand of 5.68 MW that could still be supplied due to the optional peak load supply (see Section 2.2.3). However, these alternative community combinations are unfavourable for separation due to the large distance to the waste heat source, as the costs for the necessary connection pipe between the separated DH network and the utilised heat source rise with increasing distances, which has a great impact on the optimisation objective.

In Fig. 6, the heat supply of the separated DH network is shown, divided into the HP supply $\dot{Q}_{\mathrm{HP,cen}}$, which is composed of the utilised heat source $\dot{Q}_{\mathrm{UHS}}$ and the power supply to the central HP $P_{\mathrm{el,HP,cen}}$, and the peak supply through the remaining DH network $\dot{Q}_{\mathrm{peak}}$. In addition, the temperature level of the utilised heat source T_{UHS}, the ambient temperature T_{amb} and the DH supply temperature T_{net} are displayed. The operating results are displayed in relation to the twelve operating points optimised in the model (see Table A.4) and are sorted by ascending ambient temperature.

At low ambient temperatures, high supply temperatures above 80 °C are required in the buildings supplied, which must be provided by the DH network and thus by the central HP. However, due to the lower required temperatures of the buildings at higher ambient temperatures (see Table 1), the supply temperature of the separated DH network can also be reduced, as can be seen from the comparison of the trajectories of T_{net} and T_{amb} in Fig. 6. The peak supply through the remaining DH network supports the heat supply at the highest heat demand. However,

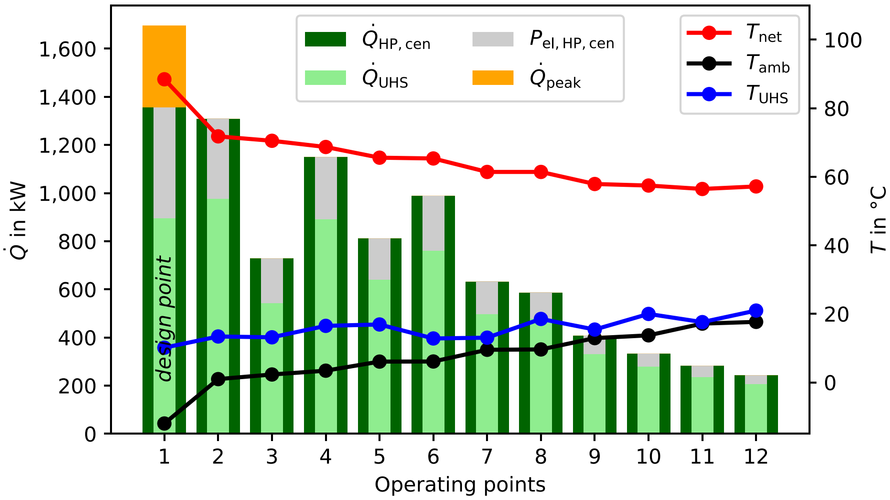

Fig. 6. Heat supply and temperatures of the separated Bottrop DH system for a 5 MW utilised heat source concerning the twelve operating points considered in the optimisation model. Operating point 1 represents the design point with maximum heat demand.

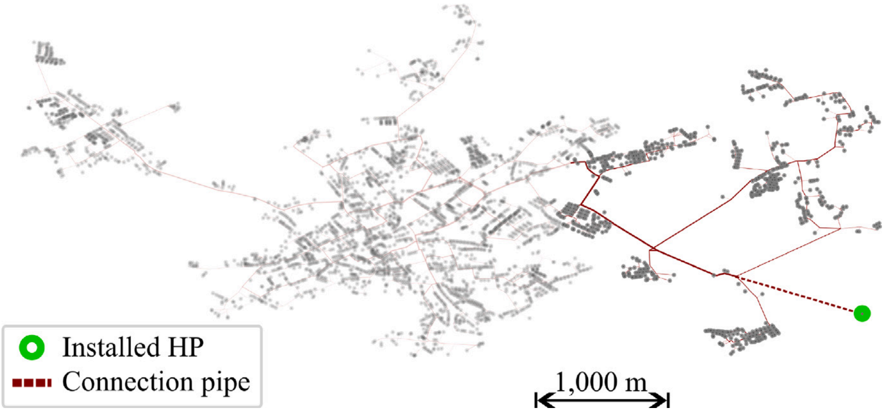

Fig. 7. Bottrop DH network separation utilising a 20 MW heat source.

the HP capacity of 1.36 MW is high enough to meet the heat demand in the other operating points alone.

The evaluation of the DH network separation through the DH simulation of the separated and the remaining DH network shows that critical bottlenecks do not occur in any of the arising DH networks. This is due to the favourable network separation since no critical distribution pipes are removed from the remaining network. In addition, the connection pipe from the utilised heat sources ties in at an existing pipe with a large pipe diameter, which favours the mass flow distribution within the separated DH network. However, the evaluation of the supply temperature reaching the supplied buildings shows that some buildings are partially supplied with too low supply temperatures. This is due to the fact that the actual heat losses are higher than assumed in the optimisation model. However, the partially insufficient temperature supply mainly occurs in summer, when the heat demand is low, which leads to high relative heat losses caused by the small mass flows, which in turn leads to high temperature drops in the DH network.

4.1.2. 20 MW waste heat potential

Assuming a larger waste heat potential of 20 MW utilisable at the sewage plant, a much larger DH network separation is possible, which is shown in Fig. 7. Since the nominal heat supply in this case is 14.67 MW and the central HP capacity is at 11.74 MW, the utilised waste heat is again not maximised.

The operating results are shown in Fig. 8, which are quite similar to the results described above, as a central HP is again installed to supply the separated DH network. The peak load supply $\dot{Q}_{\text{peak}}$ at design operating point 1 does not extend the available heat source capacity, as the 20 MW are not fully utilised, but limits the required HP capacity and thus the costs for construction. This aspect also applies to the 5 MW use case, as can be seen in Fig. 6. The DH simulation of both arising DH networks again shows that no critical bottlenecks occur in the separated or the remaining DH network, however, the buildings with partial insufficient supply can also be identified in this case.

4.2. Separation of Essen DH network utilising electrolyser waste heat

The community structure identified in the original DH network structure is shown in Fig. 9, while the optimal DH network separation result is shown in Fig. 10 and summarised in Table 3.

A network area near the location of the waste heat source is separated to limit the investment for the connection pipe. A nominal heat supply of 19.42 MW shows a much higher utilisation rate of the waste heat than in the case of the Bottrop DH network separation. The peak supply of 3.88 MW by the remaining DH network even increases the available heat from the heat source, so that the nominal supply to the separated DH network is minimally higher than the waste heat capacity of 17.5 MW (see Table 3).

Fig. 11 shows the operating results. Although the waste heat temperature is relatively high at 70 °C, the temperature level is not high enough to supply each consumer node in the separated DH network directly, since the highest temperature requirements are 85 °C at

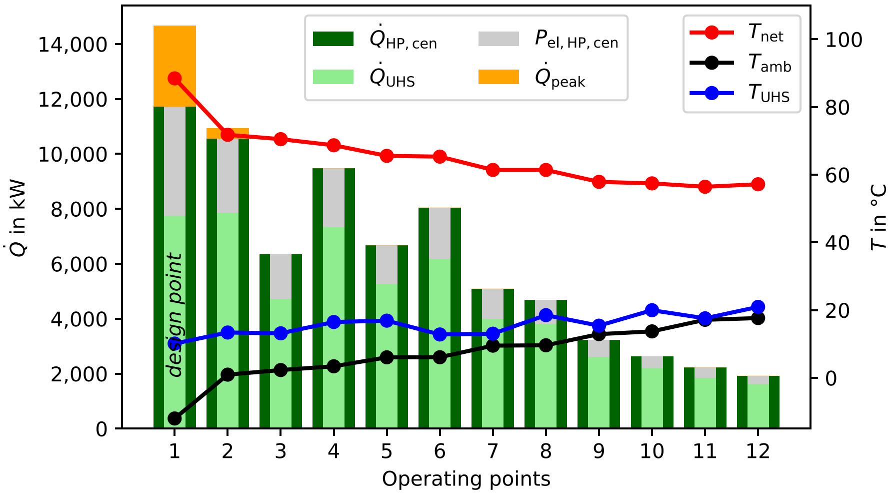

Fig. 8. Heat supply and temperatures of the separated Bottrop DH system for a 20 MW utilised heat source concerning the twelve operating points considered in the optimisation model. Operating point 1 represents the design point with maximum heat demand.

Table 3
DH design of the separated Essen DH network for a 17.5 MW utilised heat source. The costs are stated in thousands of euros (TEUR).

	17.5 MW waste heat
Total annualised costs	66,443 TEUR/a
IDs of communities separated	40, 67, 69
No. of consumer nodes separated	140
No. of decentral HPs	0
Nominal central heat supply	19.42 MW
Central HP capacity	15.54 MW
Decentral HP capacity	0 MW
Max. peak load supply	3.88 MW
DH supply temperature	79–104 °C

−12 °C ambient temperature. Therefore, a central HP is required at the electrolyser to increase the temperature level of the waste heat to a sufficient level on the coldest day. Due to the modelling approach of the HP component, there is a constant temperature difference between the waste heat temperature T_{UHS} and the DH supply temperature T_{net} at operating points 2 and 4–12 (see Fig. 11). At operating point 3, however, the temperature level is quite high, which can be attributed to the remaining optimality gap of 2.13 %.

Although the nominal capacity of the waste heat source is at 17.5 MW, the full potential is not used to supply the separated DH network because the waste heat supply fluctuates as a result of the operation schedule of the electrolyser. For example, the available waste heat at operating point 3 is limited to 9.02 MW (see Table A.5), so the peak supply from the remaining DH network must support the heat supply with 2.01 MW at this operating point, as shown in Fig. 11. However, since the possible heat energy supplied from the peak supply is restricted to 10 %, the partially limited waste heat supply, e.g. at operating point 3, limits the separation of a larger DH network.

The simulation results of the separated DH network are shown in Fig. 12. The most critical part of the separated DH network structure is the northern pipe section of the network, where pipe segments are identified as bottlenecks with pressure losses of up to 1726 Pa/m. As can be seen from the original DH network structure (see Fig. 3), the affected pipes are part of a loop and are therefore not designed for main

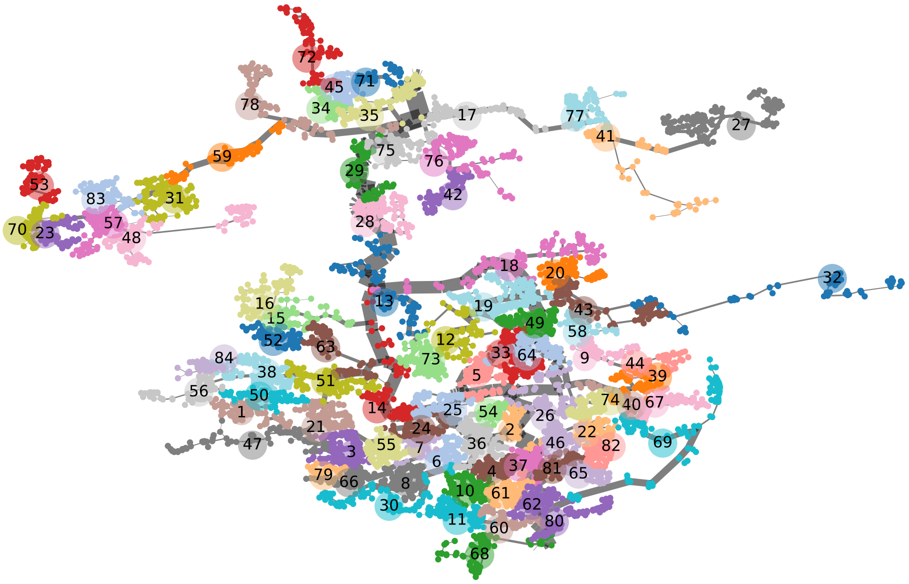

Fig. 9. Community structure of the Essen DH network detected by the Girvan-Newman algorithm.

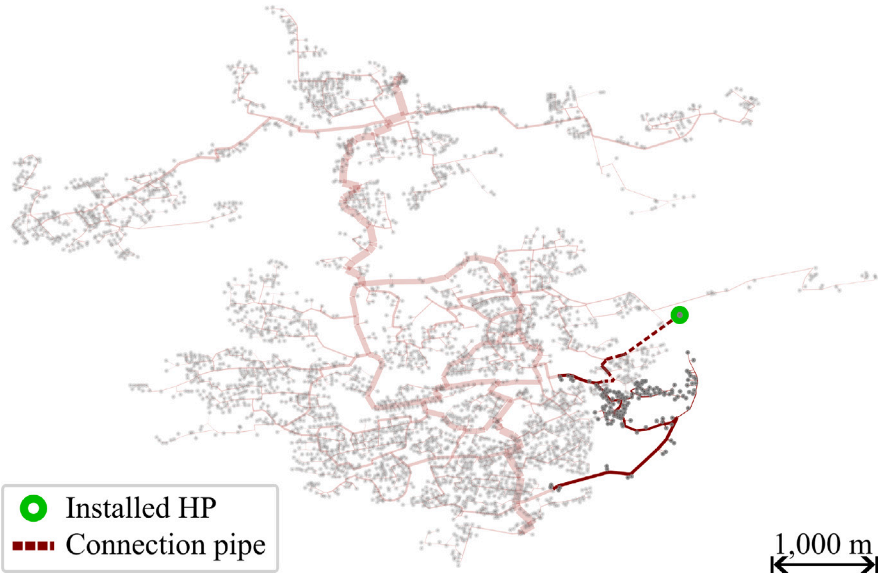

Fig. 10. Essen DH network separation utilising a 17.5 MW heat source.

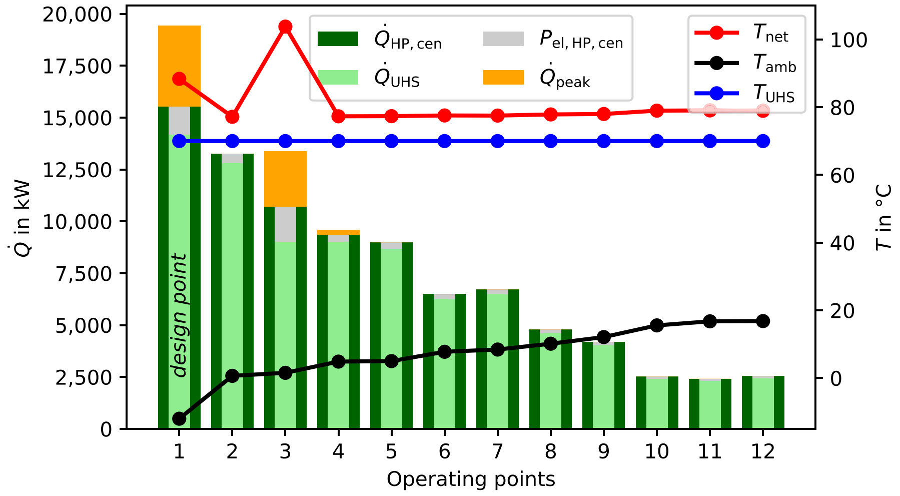

Fig. 11. Heat supply and temperatures of the separated Essen DH system for a 17.5 MW utilised heat source concerning the twelve operating points considered in the optimisation model. Operating point 1 represents the design point with maximum heat demand.

heat distribution, but to increase the security and flexibility of supply in this part of the network. However, the rest of the separated DH network structure is suitable for the required mass flow distribution. A small number of insufficiently supplied consumer nodes, shown as blue nodes in Fig. 12, are identified in the south of the separated network. These consumer nodes are affected because they are far away from the heat integration point, resulting in high temperature losses along the pipes to the consumer nodes. The simulation results for the remaining DH network are shown in Fig. 13, where some consumer nodes at the outer end of the DH network structure are identified with too low supply temperatures. However, no bottlenecks are identified in the remaining DH network, since no important distribution pipes are separated. Various measures to avoid critical areas in the arising DH networks are already being discussed in [32].

5. Discussion

In this section, the optimisation of large DH networks separation is analysed, followed by a discussion on unfavourable community detection.

5.1. Optimisation of large district heating networks separation

The adaptions to the approach of DH network separation described in Section 2 make all three steps applicable to analyse large DH networks with several thousand supplied buildings. However, the performance of the optimisation model is affected by the increasing model size. The increased model size leads to longer solution times and larger remaining optimality gaps, e.g. the remaining gap is 2.13 % in the Essen case and 1.06 % to 2.28 % in the Bottrop cases after twenty hours of computing time. By comparison, small DH networks with a hundred buildings can be optimised to global optimality (≤1 % gap) in a few minutes [32]. For larger network structures, an increasing number of integer variables must be taken into account, i.e. design decisions for the supplied buildings. Furthermore, the total number of communities and thus the number of realisable community combinations increases with the network size, leading to an additional increase in integer variables and thus in model size, which in turn leads to longer solution times. Nevertheless, the optimisation finds decent optimal solutions with small remaining gaps for large models, as the solver is able to branch the solution search tree quite efficiently. These optimal solutions are found by determining the design decisions

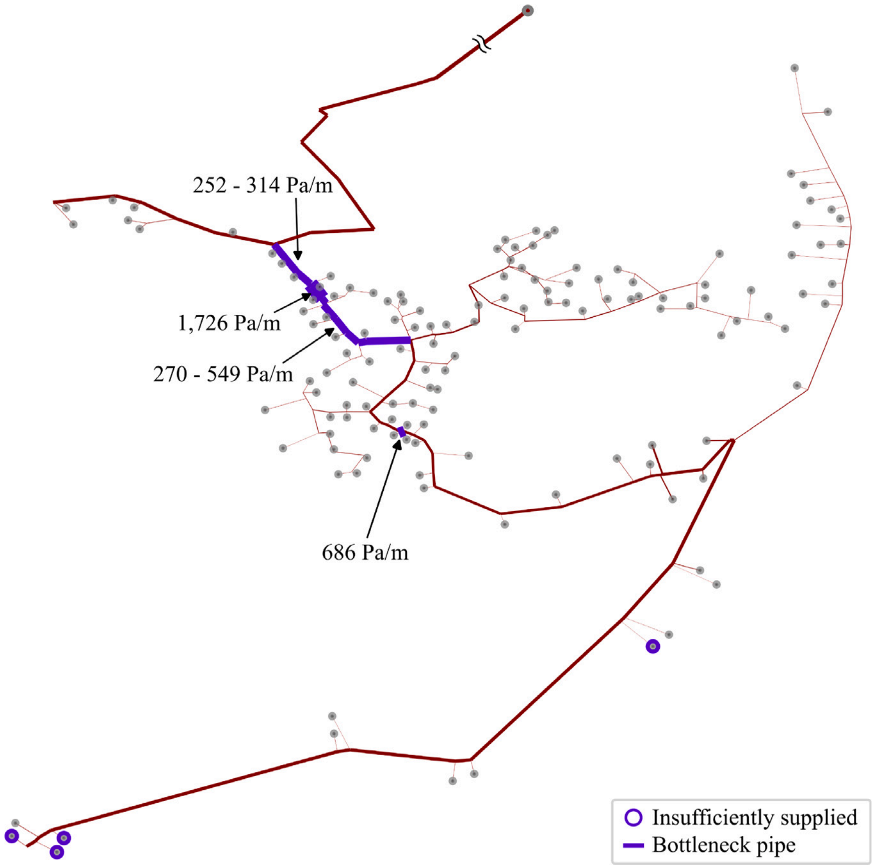

Fig. 12. Bottlenecks and insufficiently supplied buildings at separated DH network.

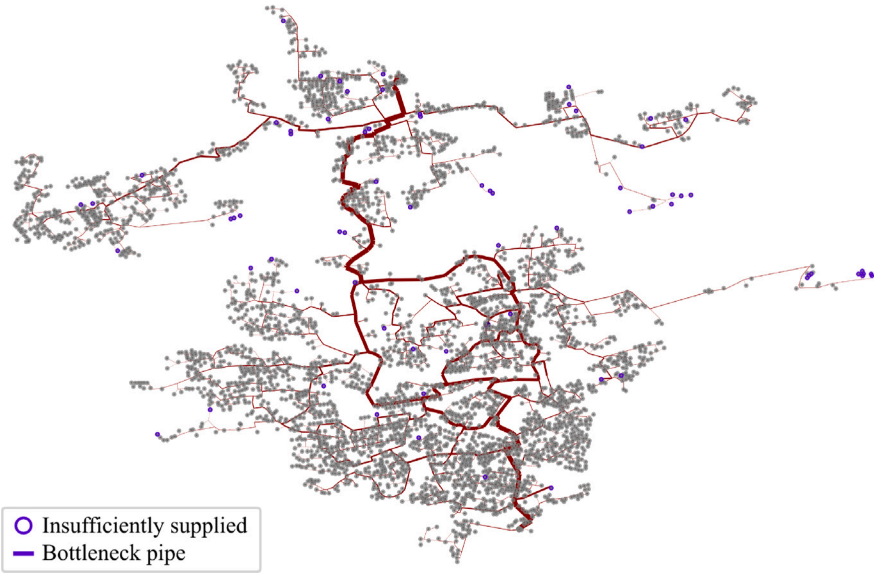

Fig. 13. Bottlenecks and insufficiently supplied buildings at remaining DH network.

that have a high impact on the objective, e.g. the decision on network separation including the costs for the connection pipe or the installation of HPs. In contrast, the operational optimisation of the DH components, e.g. HP operation or determining DH supply temperature, is more time-consuming, which increases the difficulty of achieving global optimality for large networks with a high number of buildings. However, it should be noted that the optimality gap for deterministic optimisation is an indicator that represents the minimum quality of the solution obtained, i.e. the solution found may even be global optimality or closer to it than indicated by the remaining gap.

5.2. Unfavourable community detection

In the analysis of separating the DH network of Bottrop, the unfavourable distribution of communities in the community structure determined by the Girvan-Newman algorithm leads to the fact that only a small community combination can be separated and thus only a fraction of the available waste heat is utilised (see Section 4.1.1). The application of an alternative community detection algorithm could lead to a more favourable community structure in the specific DH network area analysed. However, in another network area, the distribution of communities might also be unfavourable, i.e. the favourability for network separation depends strongly on the network structure and the area analysed.

Applying a community detection algorithm as a first step to identify coherent areas for separation is nevertheless crucial as it limits the number of options for network separation and thus enables computability. Imagine that the aggregation of neighbouring building nodes that are directly connected by pipes is used to identify areas that can optionally be separated, i.e. starting from one building in the network and meeting each neighbouring building through the existing pipe network. Since the number of possible community combinations in the analysed networks already reaches the computational limits of usually available computing resources, the consideration of an even larger number of possible building combinations for network separation is not manageable. Therefore, the application of a community detection algorithm, which pre-defines coherent areas in the DH network, is necessary to achieve a manageable number of options for DH network separation.

An advanced approach to mitigate unfavourable distribution of communities could involve subdividing individual communities that are responsible for limiting the number of realisable community combinations. For example, in the network structure of the Bottrop DH system, community 26 could be further subdivided into sub-communities, which would add a multitude of additional realisable community combinations in the network area of interest. Alternatively, communities near the utilised heat source can generally be subdivided into a finer granularity.

5.3. Improvements of the framework

Although the proposed framework demonstrates promising and useful results, two key aspects could be improved in future developments. First, in the community detection step, the building characteristics, e.g. the individual temperature requirement of the supplied buildings, are currently not considered. For example, a homogeneous local distribution of low temperature requirements in one part of the network could be considered and prioritised as an optional network area for separation. An approach integrating temperature requirements into the algorithm for community detection has already been proposed by [30], and incorporating similar approaches could strengthen the framework and enhance the results of DH network separation. Second, the utilisation of multiple heat sources in DH network separation represents an essential direction for future research. Accounting for multiple heat sources would enable a more comprehensive partitioning of DH network structures and thereby promote further decentralisation of DH systems.

6. Conclusion

A comprehensive approach for determining optimal DH network separations is further developed in this work to enable its application to large DH networks. To identify coherent areas in the DH network structure, communities are identified and aggregated into combinations of communities that are realisable for separation. To handle the extensive number of community combinations in large network structures, an efficient recursive search algorithm is applied and extended to consider the available heat source capacity. The subsequent optimisation model determines the optimal community combination for separation in terms of total annualised costs. In addition, the installation of HPs is optimised to enable the utilisation of low-temperature heat sources while still providing sufficient heat supply to existing buildings with high temperature requirements. Finally, an alternative simulation model is implemented to evaluate the operation of the arising DH networks, as the large DH networks analysed require a simplified simulation approach.

The expanded approach of DH network separation is applied to two large DH systems with over four thousand supplied buildings. The results show that the overall approach is applicable and identifies optimal DH network separations with small optimality gaps. The increased computing time is acceptable given the nature of design optimisation. The subsequent evaluation of the arising DH networks through the DH simulations reveals some critical areas in operation, from which additional necessary measures can be derived for the separated and remaining DH network.

The presented approach of DH network separation shows an alternative way to partially transform large existing DH systems. Based on the local availability of a utilised heat source, an optimal DH network area is chosen for separation and the separated DH network is operated efficiently as the DH temperatures are coordinated depending on the low-temperature level of the heat source and the temperature requirements of the separated buildings. In this way, the comprehensive transformation of the entire DH system, which is associated with a large number of obstacles and a high level of effort, is mitigated and divided into a step-wise DH transformation.

A limitation of the presented framework is that building characteristics, such as individual temperature requirements, are not yet considered in the community detection step. Additionally, it is shown that the identification of coherent network areas can be further developed by additionally subdividing the communities of greatest interest to avoid unfavourable realisable combinations of communities that result in limited utilisation rates of heat sources. Furthermore, the presented results do not account for the utilisation of multiple heat sources in the separation of district heating networks. These aspects represent important opportunities for further development and will be addressed in future work.

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, Methodology, Project administration, Funding acquisition. **Dirk Müller:** Writing – review & editing, Supervision, 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.

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Data availability

The authors do not have permission to share data

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Appendix A. Clustered operating points used as input for the optimisation model

The operating points, which are optimised in the optimisation model, and the associated weights w_t are shown in Tables A.4 and A.5. To highlight the differences between the operating points, the considered input data to determine the clusters is also shown: The ambient temperature T_{amb}, the available heat from the utilised heat source $\dot{Q}_{\mathrm{UHS}}$, its available temperature level T_{UHS} and the total heat demand of the DH network $\dot{Q}_{\mathrm{net}}$.

Table A.4
Operating points with their corresponding weights and input data, which are considered during optimisation for Bottrop DH network separation.

Operating point	w_t	T_{amb} in °C	$\dot{Q}_{\mathrm{UHS}}$ in MW	T_{UHS} in °C	$\dot{Q}_{\mathrm{net}}$ in MW
1	0.000	−12.00	5/20	10.12	74.66
2	0.093	0.95	5/20	13.39	56.97
3	0.057	2.30	5/20	13.15	31.40
4	0.052	3.41	5/20	16.49	49.15
5	0.079	6.06	5/20	16.89	33.70
6	0.089	6.09	5/20	12.81	41.44
7	0.114	9.51	5/20	13.04	25.20
8	0.103	9.61	5/20	18.51	23.04
9	0.085	12.91	5/20	15.41	14.99
10	0.106	13.72	5/20	19.97	11.72
11	0.090	17.14	5/20	17.58	9.47
12	0.131	17.65	5/20	20.95	7.80

Table A.5
Operating points with their corresponding weights and input data, which are considered during optimisation for Essen DH network separation.

Operating point	w_t	T_{amb} in °C	$\dot{Q}_{\mathrm{UHS}}$ in MW	T_{UHS} in °C	$\dot{Q}_{\mathrm{net}}$ in MW
1	0.000	−12.00	17.50	70	339.02
2	0.051	0.66	16.97	70	238.75
3	0.083	1.55	9.02	70	243.20
4	0.113	4.87	9.03	70	173.67
5	0.077	5.01	17.09	70	160.27
6	0.034	7.77	12.94	70	114.88
7	0.136	8.43	8.86	70	121.41
8	0.082	10.15	17.24	70	83.15
9	0.104	12.11	9.01	70	73.65
10	0.065	15.56	12.79	70	40.25
11	0.161	16.76	9.00	70	38.98
12	0.095	16.83	17.21	70	41.35

Appendix B. Optimisation problem size

All optimisation problems can be solved within a set time limit of twenty hours with an optimality gap of 2.5 %. The optimisation problem is solved on a Windows 10 Enterprise machine with an Intel Core i7-9700 CPU and 32 GB RAM using Gurobi 11.0.1 [38]. The size of the optimisation problem is summarised in Table B.6. The problem size and the associated solution time as well as the convergence of the problem are discussed in Section 5.

Table B.6
Variables and bilinear constraints in optimisation problem of all three analysed DH network separations.

Analysed DH separation	Bilinear constraints	Continuous variables	Integer variables
Bottrop 5 MW waste heat	32,952	98,040	2643
Bottrop 20 MW waste heat	29,460	77,628	2611
Essen	38,628	114,458	3189

Appendix C. Analysis of Bottrop DH network

See Figs. C.14 and C.15.

Appendix D. Analysis of Essen DH network

See Figs. D.16 and D.17.

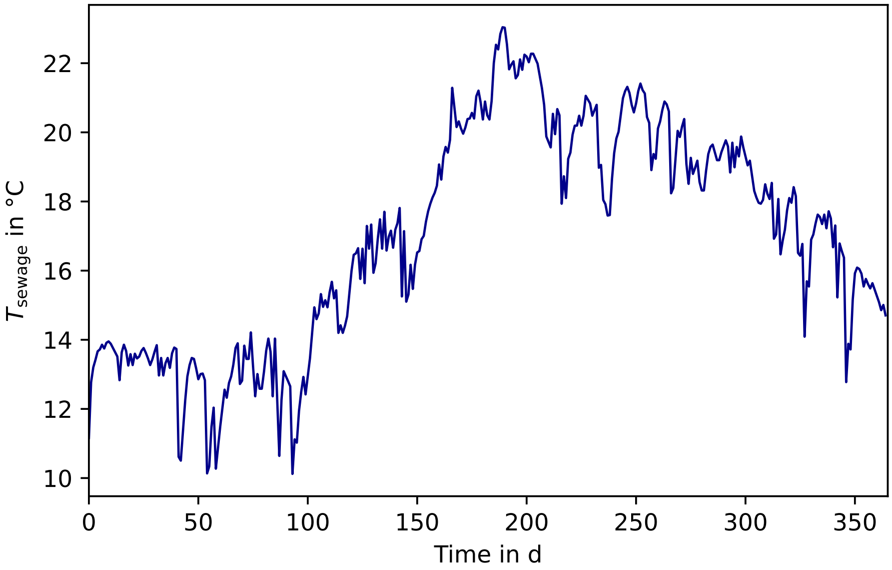

Fig. C.14. Temperature of sewage water used as a waste heat source. Values are based on [44].

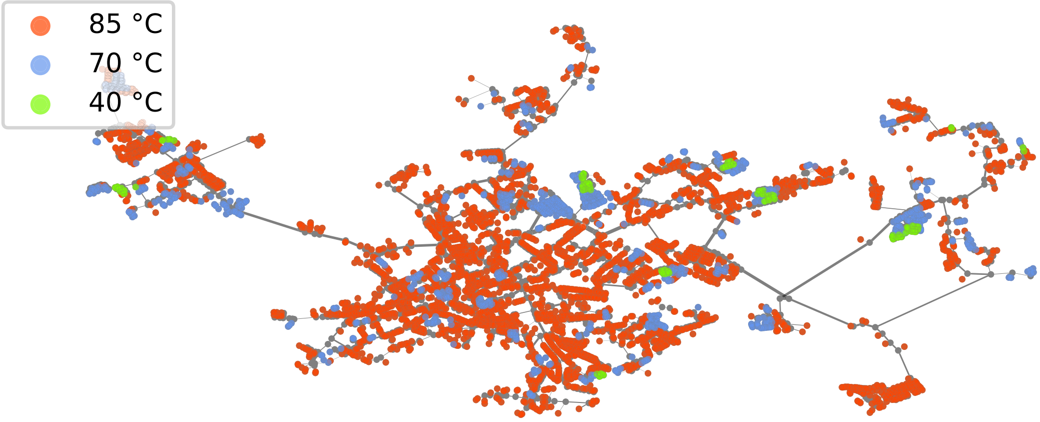

Fig. C.15. DH network of Bottrop including the maximum temperature requirements assumed at the heating systems of the supplied buildings.

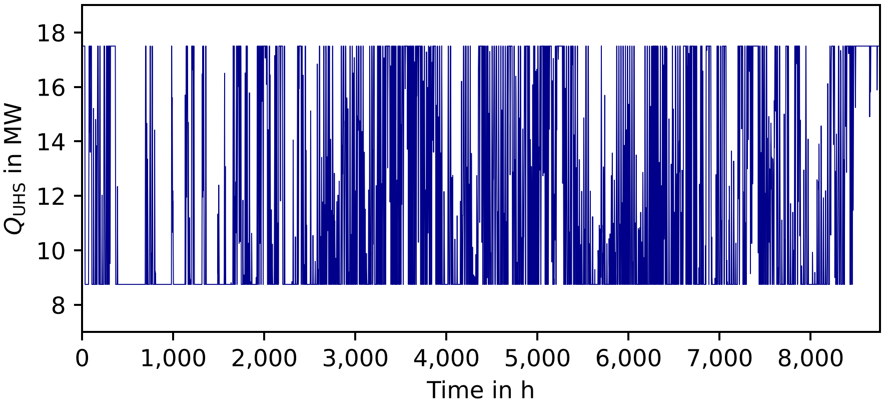

Fig. D.16. Available waste heat by the electrolyser near the Essen DH system. The operation schedule of the electrolyser is derived from the electricity prices of [47].

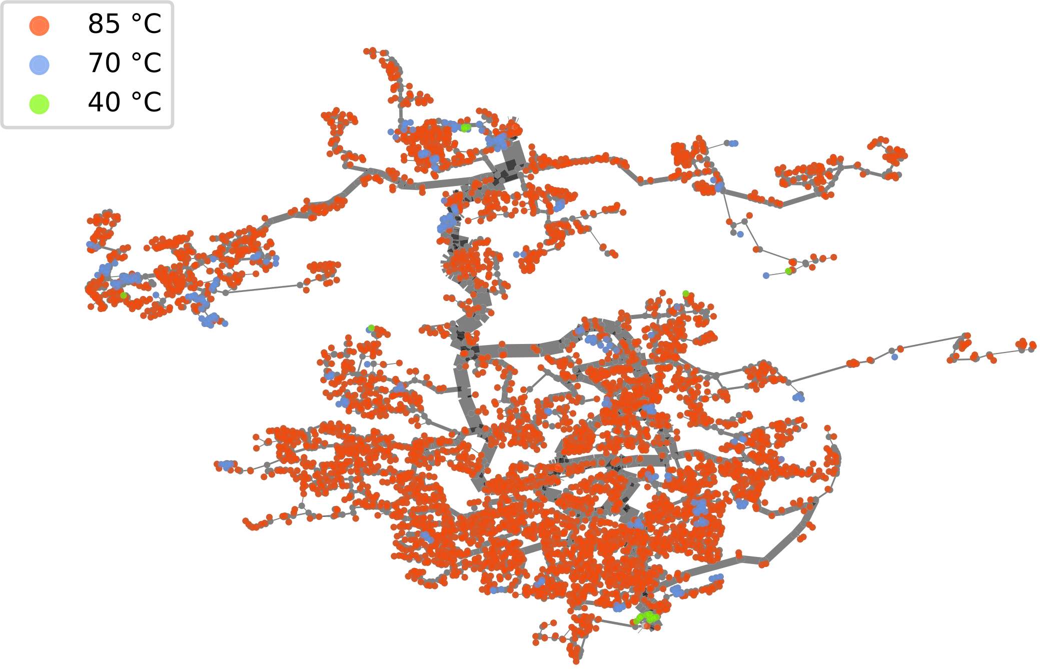

Fig. D.17. DH network of Essen including the maximum temperature requirements assumed at the heating systems of the supplied buildings.