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# Framework for the Automated Identification of Possible District Heating Separations to Utilise Present Heat Sources Based on Existing Network Topology

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**Abstract:** The ambitious climate targets of the European Union emphasise the necessity to reduce carbon dioxide emissions in the building sector. Therefore, various sustainable heat sources should be used in existing district heating systems to cover the heat demands of buildings. However, integrating on-site heat sources into large existing district heating networks could be challenging due to temperature or capacity limitations since such large district heating systems are often supplied by large fossil-based heating plants. Most sustainable heat sources that should be utilised in district heating systems differ in their geographical locations or have limited heat capacities and, therefore, cannot easily replace conventional heating plants. The resulting difficulty of integrating limited heat sources into large district heating networks could be tackled by separating the existing network structure into two independent heat distribution networks. In this study, we present a developed framework that automatically recommends which network parts of an existing district heating system could be hydraulically separated in order to utilise a present heat source that is not yet in use. In this way, a second, standalone district heating system, supplied by the utilised heat source, could be established. The framework applies a community detection algorithm to the existing district heating network to first identify communities in the structure. Neighbouring communities are aggregated to larger network areas, taking into account that these areas could be supplied with the available amount of heat. These network areas are classified as possible areas for separation if the shortest connection path to the utilised heat source is within a certain distance. Subsequently, the found possibilities for network separation are simulated to test a feasible district heating operation and to evaluate the environmental and economic impacts. The presented framework is tested with a meshed and a spanning-tree network structure. Overall, the developed framework presents an approach to utilise present heat sources in separated network structures by automatically identifying, testing and evaluating possible network separations.

**Keywords:** district heating; heat utilisation; network; community detection; separation



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## 1. Introduction

In the context of the climate crisis and rising energy demands, it is becoming increasingly important to use fossil-free energy. A significant energy consumer in Germany is the building sector where 32% of the end-energy was consumed in 2021 by space heating and domestic hot water preparation [1]. For the transition toward fossil-free heat supply in the building sector, district heating systems offer great advantages in utilising sustainable energy sources. The heat is distributed through a pipe network by heated water from one or several heating plants to the connected consumers. Nowadays, the supply of district heating systems in Germany is mainly covered by fossil-based heating plants such as combined heat and power (CHP) units or heat only boilers (HOB) [2,3]. However, modern district heating systems should incorporate renewable energy sources and operate at a lower temperature to enable more efficient heat distribution.

Lund et al. [4] introduce different generations of district heating systems mainly characterised by their working fluids and operating temperatures. Most existing district heating systems in Germany still operate at high-temperature regimes of about 100 °C [5]. These systems could be allocated to the 2nd and 3rd generations of district heating systems, depending on their actual temperature range and other system characteristics such as installed distribution pipe types. The current high supply temperature is often historically related because fossil fuel-based heating plants still supply most systems. In Germany, for example, about 70% of the heat provided in district heating systems is based on coal or gas [3]. However, fossil fuel-based energy carriers should be reduced in order to decrease carbon dioxide emissions in district heating systems. Therefore, such energy carriers must be replaced by more sustainable energy sources while maintaining the security of supply. In addition, a transition to lower operating temperatures and thus more efficient operation of district heating systems is necessary to save energy and reduce costs. With the transformation process of district heating to modern systems, the operating temperature tends to lower supply temperatures below 70 °C . These systems are called the 4th generation of district heating or low-temperature district heating networks [4]. The low supply temperatures ensure the 4th generation system to utilise various low-grade heat sources at a low-temperature levels.

In order to spread the concept of 4th generation district heating, the integration of sustainable heat sources into existing network systems and the adaption towards lower supply temperatures is essential to enable the above mentioned advantages. In the following, different studies and approaches are summarised in terms of how existing district heating systems could be transformed to 4th generation systems and sustainable heat sources at a low-temperature level could be integrated.

### *1.1. Transformation of Existing District Heating Systems*

Most available sustainable heat sources that should be used in district heating are available at low-temperature levels, such as waste heat sources from different processes or facilities, e.g., industrial excess heat from the food production process or the waste heat of a cooled data centre [6]. Furthermore, most used renewable energy sources in district heating systems are available at a low-temperature level, such as geothermal energy sources or solar heat [7]. Using heat sources at an ambient temperature level, such as ambient air or water from lakes and rivers, is also possible by upgrading the temperature with heat pump systems to a sufficient supply level for the district heating systems [8,9].

The transition process of existing district heating systems to lower supply temperatures is already frequently investigated. Rämä et al. [10] describe the transformation process of high and medium-temperature district heating systems and occurring barriers such as temperature requirements of the connected buildings or rising mass flow rates in the pipe system. In [11], different adaptions to district heating systems and to their connected consumers are studied by simulations. The transformation of district heating systems in areas with different heat demand densities is investigated by Nord et al. [12]. They show that district heating transformation leads to lower heat losses, especially in areas with high heat demand density, but the pump energy consumption increases due to rising mass flows. In [13], different transition levels for the transformation of an existing district heating system until 2050 are designed, including gradual temperature reduction and increasing the use of waste heat of a high-performance computing (HPC) facility.

The usual way to make use of upcoming heat sources in existing district heating networks is to integrate them as additional, decentralised heat sources to support the conventional heating plant and, in case of fossil-fuel based plants, to reduce its emissions. Oltmanns et al. [14] use such available waste heat source to reduce the carbon dioxide emissions of a district heating system supplied by a CHP. The waste heat is integrated into the return line of the existing district heating system, resulting in a reduction of carbon dioxide emissions associated with heat distribution. Rämä et al. [15] study the integration of additional solar collectors and heat pump systems into the CHP supplied district heating system of Helsinki. In [16], the general effects of integrating an additional heat pump into a district heating system are evaluated. It was found that the heat pumps bring flexibility to the district heating operation and have a positive impact on the electricity market. However, ref. [17] shows limitations of additional heat source integration as they investigate the integration of waste heat into a district heating system placed at the university campus in Trondheim. They evaluate how the additional heat integration affects the network performance in terms of hydraulic and thermal effects. In particular, the emergence of pressure cones at the new integrated heat source affects the reliable heat supply to some consumers in the network.

Another possibility to establish low-temperature district heating networks in existing network infrastructures is the creation of so-called subnetworks [18,19]. Subnetworks are network structures within the primary district heating system that usually operate at a lower temperature level than the rest of the network. These subnetworks are typically supplied via the primary network but are hydraulically decoupled from it. Usually, low-temperature subnetworks are supplied via the return line of the primary high-temperature network. As an example, Winterscheid et al. [20] investigate a subnetwork, which is mainly supplied by solar thermal systems and the connection to the primary district heating network.

### *1.2. Challenges of Using Available Heat Sources in District Heating Systems*

Most district heating systems are extensive and have large networks to distribute the heat to many connected consumers. For example, 86% of district heating systems in Germany have total network lengths of about 100 km [21]. Such large network systems are often supplied by one or a few big fossil-based plants with large heat capacities. However, as mentioned above, most of the available sustainable heat sources under consideration have limited capacities that can not meet the total heat demand of all consumers connected to an extensive district heating system. In addition, the fixed geographical location of the heat sources to utilize usually differ from the locations of the current heating plants. This makes the integration of such heat sources even more difficult, because of possible poor topology connectivity, e.g., the closest network pipes to the heat source have insufficient diameters, and thus, limiting the amount of heat that can be integrated. Therefore, replacing large fossil-based heating plants by integrating various available heat sources in current district heating systems is challenging.

An approach to facilitate the integration of sustainable heat sources into an existing district heating system and to gradually replace current large heating plants could be to split the district heating network. A small part of the existing network structure could be separated from the main network to create two fully isolated subnetworks, one supplied by a utilised sustainable heat source and the other continuing to be supplied by the current heating plant. In this way, large centralised district heating systems can be decentralised to several smaller systems. Such decentralised district heating systems can operate more efficiently due to lower heat losses and can utilise various distributed heat sources with small heat capacities, which are frequently available [6].

Furthermore, the challenging integration of low-temperature heat sources, due to the usually large temperature gaps to current district heating operating temperatures, could be more easily managed by decentralising district heating networks. When networks are separated, the utilisation of low-temperature heat sources does not affect the entire district heating system because the temperature does not have to be upgraded to the highest temperature requirement in the large network. The separated network could be adapted more efficiently and reasonable to the lower available temperature level by adapting the separated consumers, such as lowering their temperature requirements.

The approach of separating existing district heating systems is not widespread. In [22], an available waste heat source of a HPC facility is used by separating buildings and pipes from a high-temperature district heating system to implement a separated low-temperature system with decentralised heat pumps. Another approach for dividing a network into different parts is presented by [23]. They do not separate the network physically, but outline regions in the network structure that could be separated by valves and pumps to improve heat distribution control.

However, the approach of detecting different areas in a network structure to separate the network into several parts that are easier to measure and control is very common in other types of distribution networks. For instance, water distribution networks are separated into so-called district metered areas to monitor different parts of the network and to detect possible leakages in the network structures fast and precisely. For this purpose, these areas in a water distribution network are detected by various cluster algorithms and then are sectorised by installing valves and flow meters between these areas. Through these isolated areas of the network, the entering and leaving water volumes can be measured and possible water leakage can be more easily detected and managed [24].

### *1.3. Aim of Work*

Derived from the idea of separating existing district heating networks to decentralise large systems and to use heat sources with limited heat capacity, including the approach of clustering distribution networks to identify areas in the structure, we develope a framework that identifies possible network separations depending on the studied district heating system and the characteristics of the heat source that should be utilised. This developed framework automatically reveals which parts of an existing district heating network should be separated to create a new decentralised district heating system that uses the already installed pipes but is supplied independently by a new heat source.

The paper is organised as follows. In Section 2, we introduce the general idea of community detection in network structures. In the following, we demonstrate the developed framework for an automated and efficient network separation to generate different possible separation scenarios. We also present the used assessment approach to evaluate the developed separation scenarios. Section 3 describes the use-cases and corresponding network structures we use to demonstrate our developed framework. The resulting possible network separations and their environmental and economic evaluation are presented in Section 4. After a brief discussion in Section 5, we draw a conclusion in Section 6 and give an outlook for further research.

## 2. Methodology

In our approach, we wanted to identify possible network parts of a large network structure that can be separated from an existing district heating system to establish a new separated district heating network supplied by a new, either upcoming or present, heat source. In the context of energy transition and the concept of 4th generation district heating, we focused on heat sources that mostly provide heat at low-temperature levels, mainly renewable energy or waste heat sources. Thus, heat sources in this context could be a geothermal field, a solar thermal collector or a building which emits a lot of waste heat such as a supermarket or a data centre. The sites of these described heat sources are usually fixed due to different constructive or regulative boundary conditions. Therefore, the possible identified parts of the network should be near the location of the new heat source to avoid long connection pipes between the heat source and the separated network system.

Furthermore, the framework should identify network parts by taking the estimated amount of heat and the nominal heat capacity of the source into consideration. The heat demand of the specified network parts should fit the available heat source to avoid the additional installation of supporting heating plants. As explained before, most existing district heating systems operate at a high-temperature level. Integrating a low-temperature heat source into an existing network structure is challenging. It is necessary to avoid a lack of comfort for the consumers caused by too low supply temperatures while simultaneously ensuring an efficient operation. Furthermore, the temperature difference between network supply and return temperature is often smaller in low-temperature networks. If the nominal heat demands of the buildings stay unchanged, the lower temperature difference leads to higher mass flows in the pipe system, leading to higher friction losses and therefore to increasing pump energy consumption. Therefore, a possible and appropriate temperature level of the separated district heating system has to be determined, which enables adequate heat supply to all consumers in combination with an efficient and reliable network operation. Therefore, when a low-temperature source is used to cover the heat demands of separated buildings that are designed for high-temperatures, a temperature upgrade of the utilised heat source is generally necessary.

However, although several pipes and consumers are separated from the original district heating system, the design parameters of the remaining network, concerning its temperature level, should not be altered. Therefore, both the separated and the remaining network structure must be evaluated to ensure a sufficient heat supply to the connected buildings. Furthermore, the identified network separation possibilities should be assessed to show the most beneficial separation to utilise the new heat source.

To distinguish the two resulting network parts, we refer to the detached network using the available heat source as the "separated network" supplied by the "new heat source", and to the untouched network part as the "remaining network" supplied by the existing "conventional heat source".

In Section 2.1, we introduce the concept of finding so called communities in a network structure. The used community detection algorithm in the context of this study is described in more detail in Section 2.1.2. Based on the found communities, we describe an approach for identifying possible network areas in a district heating system that can be separated from the original network structure to build a new district heating network supplied by a new heat source. After we have identified possible scenarios for network separation, we explain the simulation approach and how we evaluate the district heating operation of the identified scenarios in Section 2.2. In Section 2.3, we describe the proving of a feasible district heating operation and an assessment of the separation scenarios related to the status quo of the investigated district heating system.

### *2.1. Identify Network Communities*

#### 2.1.1. Algorithm for Community Detection

In graph theory, a network structure consists of nodes and connecting edges between these nodes. Within a network structure, groups of nodes can be identified or characterised by similar properties. These groups of nodes with similar characteristics are called clusters or communities. This characterisation of communities could be the local density of nodes within a network or the number of connecting edges between a set of nodes. Identifying these groups of nodes with similar properties is called network clustering or community detection [25].

The quality of the resulting communities in a network can be evaluated by an indicator called modularity $Z$ (in literature, the modularity is partly also assigned by Q) [25]. The modularity measures the density of a community, indicating a higher density if they are more edges within a group of nodes than there are edges to neighbouring nodes. In other words, the modularity evaluates the connections inside a community in contrast to the links between communities. The modularity is defined as:

$$Z = \frac{1}{2m} \sum_{ij} \left[ A_{ij} - \frac{k_i k_j}{2m} \right] \delta(C_i, C_j), \tag{1}$$

with $A_{ij}$ as the matrix indicating the weight of edges between node $i$ and node $j$, $k_i = \sum A_{ij}$ as the sum of weights of edges connected to node $i$, $C_{i,j}$ as the community that includes node $i$ or $j$, delta as the Kronecker delta that is equal to 1 for $C_i = C_j$ and otherwise equal to zero, and with $m = \frac{1}{2} \sum A_{ij}$.

Algorithms support the process of community detection as they can identify groups of nodes with similar properties. The properties after which communities are specified have to be defined beforehand. Many algorithms exist that are used for community detection in different kinds of networks, e.g., social internet platforms networks, mobile phone networks or water distribution networks [24,26].

In our study, we used a community detection algorithm that is suitable for the intention of district heating network separation by taking the pipes of the network, and the possible removal of them as intended, into consideration. This utilised algorithm for the presented framework is developed by Girvan and Newman [27] and further described in the following Section 2.1.2.

### 2.1.2. Girvan–Newman Algorithm

The Girvan–Newman community detection algorithm is a hierarchical community detection approach. The algorithm focuses on edges in the network that are at least central, i.e., edges between possible communities of the network. Therefore, Girvan and Newman define an edge-betweenness that symbolises how often the shortest connections of all node pairs pass an edge. The edge-betweenness of all edges are calculated by identifying the shortest paths of every node in the network to all its neighbouring nodes. An edge being part of such a shortest path raises its edge-betweenness by one. The shortest paths between two nodes is determined only by the total number of passed edges, so no edge property such as length or weight has any effect on the calculation of edge betweenness. If multiple shortest paths between to nodes exist, the edge-betweenness of the edges is raised proportional e.g., by 0.5 if two possible shortest paths exist. The shortest paths are determined for every node pair in the network while counting the passing of an edge. After the edge-betweenness for every edge in the network is calculated, the edges with the highest edge-betweenness are passed most often by the shortest paths between the nodes (see Figure 1).

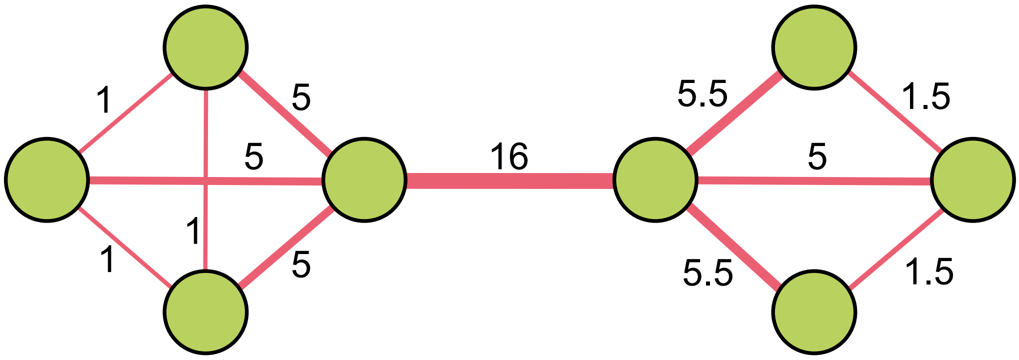



**Figure 1.** Numbered edge-betweenness in a simple graph network, visualised by various edge thicknesses (own representation based on [28]).

Edges with high edge-betweenness values represent connections between sets of nodes in the network, i.e., connectors between communities. Removing these edges with the highest edge betweenness, unveil the communities within the network structure. Therefore, the first two communities of the network are revealed by removing the edge with the highest edge-betweenness (in Figure 1 the edge with a edge-betweenness of 16). If the network has a meshed structure, multiple edges with the highest edge-betweenness are removed until two communities are revealed. The edge-betweenness and removing the edges with the highest edge-betweenness is calculated iteratively until every edge in the network is removed. Thus, every node of the network symbolises a community at the end of the algorithm.

The resulting communities and their subcommunities can be arranged in a dendrogram, symbolising the community structure of a network. With the presented algorithm of Girvan–Newman, different degrees of fineness could be chosen to identify community structures in a network. The final number and size of the communities depend on the number of removed edges or, visual spoken, depend on the layer where the dendrogram is cut. Therefore, the algorithm requires a criterion at which degree of fineness the identified community structure is suitable for the studied network structure. Usually, this criterion is the optimisation of the modularity, i.e., the resulting community detection with the highest modularity is chosen.

A district heating network can be visualised as a graph structure with nodes for connected consumers and network forks, while edges symbolise the connecting pipes. Since the Girvan–Newman algorithm identifies the communities in a network by removing edges between possible communities, this approach fits well with the intention of district heating separation. Furthermore, the Girvan–Newman algorithm is already used in applications similar to district heating networks as it is also applied to water distribution networks to identify district metered areas [24].

#### 2.1.3. Identify Possible Separation Scenarios

Based on the Girvan–Newman algorithm, we wanted to create different options for network separation. To enable the framework to study various heat source configurations such as available heat capacity or different sites, we implemented the framework with a high automatisation rate to increase the ability to study different system designs. Therefore, we implemented the various steps in the programming language Python. The entire framework for identifying possible network separations is presented in Figure 2.

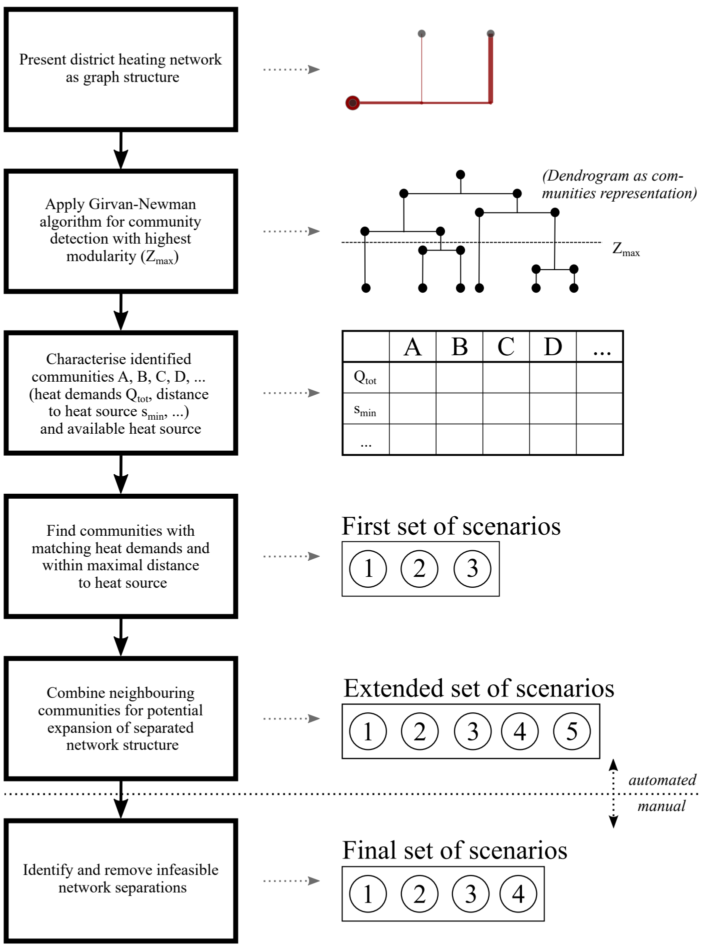



**Figure 2.** Framework for identifying possible network separations of a district heating network.

#### Network as Graph Structure

First, the district heating network was represented as a graph structure to apply the Girvan–Newman algorithm. We used the Python-based energy network tool *uesgraphs*, which handles energy network structures as graph structures by assuming consumers, energy plants and network forks as nodes and connecting distribution lines, e.g., network pipes as edges [29].

Identify and Characterise Network Communities

Second, we applied the described Girvan–Newman algorithm to the graph structure to identify communities in the network. The Python package *NetworkX* (https://networkx.org/, accessed on 3 August 2022) offers a method to apply the Girvan–Newman algorithm to graph structures. The modularity of the community detection could be calculated by a method also implemented in the *NetworkX* package. The community detection with the highest modularity was chosen to perform the following steps of specifying the possible parts for network separation. The identified communities in the network structure were characterised depending on their included buildings and distribution pipes. We summarised the heat demands of all included consumers in a community $Q_{tot}$ by available heat demand measurements or heat demand simulations of the supplied buildings. In addition, we summarised the maximal required heat supply $\dot{Q}_{max}$ of all included consumers in the community, deduced from the available heat demand data. While determining $Q_{tot}$ and $\dot{Q}_{max}$ for all communities, we considered the estimated heat losses and the simultaneous factors of heat distribution. The heat losses for a community were calculated based on the expected heat distribution and the assumed temperature level [30]. The simultaneous factor, taking into account that not all consumers have their highest heat loads simultaneously, was estimated based on the included buildings in a community [31].

Furthermore, we calculated the shortest distances between the new heat source and the closest nodes of each community. We determined the shortest connection path to every community along the already installed pipes because the necessary new connection pipes between new heat source and separated district heating network could not be constructed as the crow flies.

Characterise Utilised Heat Source

In addition, we characterised the new heat source to be used as a new heating plant, as we did for the identified communities. First, the maximal heat capacity of the source was determined. If a heat pump system was required to raise the temperature at the heat source, we also took into account the additional power input. The required temperature level in the new district heating system had to be estimated depending on the investigated district heating system and especially on the heating systems of the supplied buildings. Furthermore, we calculated the total amount of heat that the new heat source could distribute.

Create Separation Scenarios

After characterising the communities and the new heat source, the next step was to identify possible parts to separate from the original network structure. Every community that has heat demands below the available heat offer is a possible community which can form a separated network structure to establish a standalone district heating system. The potential separation of a community to build a new district heating system is called a scenario. We collected possible scenarios for network separations in a set of scenarios to evaluate them later. However, we had to avoid the separation of unwanted network parts, such as parts of the network with special demands, e.g., network structures from the centre of the original network structure that are necessary for a faultless operation of the remaining network. Therefore, we could preselect nodes or areas of the original network structure, which highly depend on the investigated system, that should not be chosen for a network separation. Thus, communities that include such marked nodes or areas were not an option for network separation.

Avoid Poor Communities

Some identified communities in a district heating network are not favourable for forming a separated district heating system for different reasons. They could be far away from the new heat source, which would lead to high connection pipe installation costs, or the combined heat demand of all connected consumers in a community could be very small, which would result in a very low exploitation of the heat source potential. The determination which communities in a network are poor, so too far away or too small, is individual to the investigated district heating system. One approach could be to optimise the process of finding communities, which would automatically sort out not favourable communities because of too high cost or inefficient heat source usage. Another opportunity is setting fixed constraints for avoiding the separation of poor communities. Such constraints could be the maximal allowed distance between heat source and separated network structure or the minimal heat demand of all separated consumers. These constraints highly depend on the investigated system, such as its total network length or its topology, and therefore have to be set individually. In the scope of this study, we used this approach of setting constraints to avoid separation scenarios of poor communities.

We derived absolute constraint values, based on the investigated use-cases in this study. Therefore, we assessed different shares of network lengths to determine the maximal distance for the connection pipe between the heat source and the nearest connection point of the separated network structure. In this way, we deduced a reasonable maximal distance of 5% of the total network length as an upper limit for the connection pipe. We also assessed different shares of the available heat to determine the minimal heat that should be used by a separated community. From this, we deduced that communities with heat demands of less than 5% of the available heat should not form a standalone separated district heating system. The found relative shares of network length and heat source capacity were not general for every district heating system and were only used for the presented use-cases. For other systems, new constraints have to be set, either by testing different shares or directly setting absolute values that relate to the studied cases.

All communities with a longer distance to the source or with smaller heat demands than these set constraints were sorted out from the possible separation scenarios. However, these communities were not completely out of scope, as they can still be extensions of other communities and so be part of larger separation scenarios.

Setting the constraint values to avoid poor communities in advance is difficult because each existing district heating system is individual in terms of its length or heat demand. Another approach for avoiding poor communities without such a conducted assessment is discussed in Section 5.

Combining Communities

Next, we considered the combination of different communities to larger network structures that could be separated. For each identified community that can form a network separation, we tested the neighbouring communities for possible network extension. If the heat source could still supply the additional heat demands, a further scenario was added to the set of scenarios, now as a network structure separation consisting of two or more communities. The possible network extension by adding neighbouring communities was checked for every identified scenario from the previous step. Here, we also tested the communities too far away from the source or with too small heat demands to consider that these communities could be part of another scenario.

Final Set of Separation Scenarios

So far, each described step was automated and the set of scenarios was determined based on the district heating system and the characteristics of the new heat source. However, as a last step, we sorted out scenarios from the set of scenarios that were not feasible for network separation. For example, such an infeasible network separation could be the separation of a network part, which leads to two separated remaining network structures.

Without installing an additional pipe between the two remaining networks, which we did not consider in this study, an operation of the remaining network would not be possible in the case of just one heating plant. Thus, we checked the resulting set of scenarios for infeasible network separations and manually removed them from the set of scenarios. As a result of this framework, we obtained a set of scenarios of possible network separations, including single communities or combinations of neighbouring communities.

To prepare the network data for district heating simulation, we manipulated the *uesgraphs* structure of the original district heating network to generate two separated network structures for every separation scenario. This was carried out automatically based on the final set of scenarios. Thus, we obtained the new and the remaining district heating network of every scenario presented as a *uesgraphs* structure which were used for simulation model creation.

### 2.2. Network Simulations of Identified Scenarios

The identified separation scenarios have to be tested for a feasible operation to establish a standalone district heating system. In addition, the remaining district heating system has to be checked to still ensure a faultless network operation, despite the removed pipes that are used for the separated system. In this context, a faultless operation of a district heating system mainly means two points. First, to guarantee reliable heat supply at a sufficient temperature level to the connected buildings, and second, a feasible distribution of heat via the pipe system without too high friction losses. The district heating systems were simulated over one year of operation. To test most critical times of operation, we added a time step to the input simulation data where all connected buildings have their nominal heat demands, meaning that the highest possible heat requirements in the network arise during the same time step. By the simulation of this hypothetical operation, we could also evaluate the most demanding operation of the separated network and identify possible difficulties in the network structure.

We created district heating models in the modelling language Modelica by using the modelling approach of [29]. This approach enabled us to use the district heating network data implemented in the graph structure of *uesgraphs* to automatically generate Modelica simulation models based on individual district heating characteristics. The main network components, heating plant, distribution pipes and consumers were represented in the *uesgraphs* structure and were specified by attributes such as their capacity, design or heat demands. For all three types of components, Modelica submodels were defined and parameterised based on the specified attributes in the *uesgraphs* structure. Thus, district heating models could be generated automatically for every identified separation scenario based on the graph structures of the new and the remaining district heating systems.

After carrying out the network simulations of all separation scenarios, the results were evaluated and assessed to identify feasible scenarios and the most promising option for further investigation. We also simulated the original district heating system as a reference case to compare the different scenarios to the status quo.

### 2.3. Evaluation of Identified Separation Scenarios

As a first step, we checked the feasible heat distribution in the pipe network for all separation scenarios. In the newly created district heating system, higher mass flows are expected in the pipe network because the temperature differences between supply and return temperature are usually smaller than in the original network. Since the supplied heat must be the same as for high supply temperatures, the mass flow increases for smaller temperature differences. However, increasing mass flows may also occur in the remaining network as some of the removed pipes may have previously acted as important backbone pipes in a meshed network.

Increasing mass flows in a pipe system cause higher friction losses, leading to higher energy consumption for the circulation pump. To validate the friction losses in the pipe systems, we evaluated in which parts of the networks the specific pressure drop exceeds the recommended maximal value of 250 Pa/m [32]. The pipes where this maximal pressure drop is exceeded represent critical parts in the network or so-called bottlenecks. Such bottlenecks cause high pump energy demand and can lead to an increasing deterioration of these pipes.

We also evaluated the reliable heat supply to the connected buildings. In particular, for the newly created district heating system, a sufficient heat supply at the required temperature level must be ensured. The required supply temperature at the building side is usually controlled by a heating curve of the heating system depending on the measured outdoor temperature. This required supply temperature for the heating system should be fulfilled by the incoming supply temperature at the primary network side. Therefore, we checked the sufficient heat supply of every building in the network and identified critical buildings supplied with too low temperatures. For the temperature difference between the primary side of the network and the secondary side, symbolised by the heating system of the building, we assumed a temperature loss of 3 K.

To evaluate the different separation scenarios, we also calculated the environmental impacts and the changed economic conditions concerning the operation of both arising district heating systems. By separating consumers from the original network, the supplied heat by the conventional heating plant will be reduced. Therefore, we evaluated the changed environmental and economic conditions referring to the current status quo of the original district heating system. The measures that may be necessary as a consequence of the supply reduction of the existing heating plant, such as the retrenchment or the adaption of the control strategy, are specific to the district heating system and must therefore be evaluated individually and are not a subject of this study.

For the evaluation, we first calculated the changed energy consumption. The pump power for circulation decreases in the remaining network $\Delta P_{\text{pump,remain}}$, but at the same time, additional pump power is needed for the separated district heating system $P_{\text{pump,new}}$. Furthermore, energy for heat pump operation $W_{\text{HP}}$ is required in most cases to increase the temperature level of the mostly utilised low-temperature heat source. The power consumption of the heat pump $P_{\text{HP}}$ depends on the coefficient of performance, which could be calculated with the logarithmic temperatures of the heat source $T_{\text{lm,source}}$ and the set supply temperature $T_{\text{lm,supply}}$ of the district heating system. The actual power consumption was calculated according to:

$$P_{\text{HP}} = \frac{\dot{Q}_{\text{HP}}}{\frac{T_{\text{lm,supply}}}{T_{\text{lm,supply}} - T_{\text{lm,source}}} \cdot \eta_{\text{HP}}}, \tag{2}$$

with the supplied heat $\dot{Q}_{\text{HP}}$ of the system and the system efficiency $\eta_{\text{HP}}$, which was set to 0.5 in this study [33,34].

The amount of supplied energy by the conventional heating plant decreases because fewer buildings are connected to the remaining network, resulting in changed heat supply $\Delta\dot{Q}_{\text{conv}}$. In most cases, the conventional heating plants are fossil-fuel fired plants and the reduced heat supply results, related to the efficiency of the plant $\eta_{\text{conv}}$, in reduced gas or coal consumption. In this study, we assumed that the new heat source for the separated network is a renewable or a waste heat source with a $CO_2$ factor of zero. Based on the changed energy conditions in the networks, the changed $CO_2$ emissions,

$$\Delta CO_2 = \int_0^T \left[ \frac{\Delta\dot{Q}_{\text{conv}}(t)}{\eta_{\text{conv}}} \cdot CO_{2,\text{conv}} + (P_{\text{HP}}(t) + \Delta P_{\text{pump,remain}}(t) + P_{\text{pump,new}}(t)) \cdot CO_{2,\text{el}} \right] dt \tag{3}$$

were calculated with the time period $T$, the time step $t$ and the related $CO_2$ factors of the electricity grid $CO_{2,\text{el}}$ and for the conventional heating plant $CO_{2,\text{conv}}$ [35]. In addition, the used amount of heat from the new heat source was calculated for each separation scenario to identify the network separation with the highest utilisation of the offered heat.

Moreover, we also evaluated the changed economic conditions due to network separation that mainly affects the network operators and the specific costs of delivered heat. Therefore, we calculated the necessary investment $C_{\text{inv}}$ for the mandatory connection pipe between the new heat source and the separated network and the new required circulation pump for the separated network [36]. In addition, we considered heat pump investment and installation costs if a temperature upgrade is necessary [37].

We also calculated the change in operating costs in relation to the status quo of the studied district heating system. We assumed that the original district heating system and its heating plants were fully economically depreciated. Therefore, the changed revenues had no influence on the original project calculation. The changed operational costs $C_{\text{op}}$ were calculated as follows:

$$C_{\text{op}} = \int_0^T \left[ \frac{\Delta \dot{Q}_{\text{conv}}(t)}{\eta_{\text{conv}}} \cdot c_{\text{conv}} + (P_{\text{HP}}(t) + \Delta P_{\text{pump,remain}}(t) + P_{\text{pump,new}}(t)) \cdot c_{\text{el}} \right] dt + \dot{Q}_{\text{HP,cap}} \cdot c_{\text{HP,op}}, \quad (4)$$

based on the energy costs for electricity $c_{\text{el}}$ and the costs for the fuel of the conventional heating plant $c_{\text{conv}}$ [38,39]. In addition, the operational and maintenance costs for possible heat pump operation $c_{\text{HP,op}}$ were taken into account depending on the capacity of the installed heat pump system $\dot{Q}_{\text{HP,cap}}$ [40].

Based on the operational costs and the necessary investment, we calculated the total annualised costs ($TAC$) according to:

$$TAC = -C_{\text{inv}} \cdot \frac{(1+i)^n \cdot i}{(1+i)^n - 1} + C_{\text{op}}, \quad (5)$$

with an assumed project lifetime $n$ of 30 years and an interest rate $i$ of 3%. Furthermore, we calculated the necessary period $n_{\text{crit}}$ for the investment to amortise:

$$n_{\text{crit}} = \frac{\ln\left(\frac{C_{\text{op}}}{C_{\text{op}} - C_{\text{inv}} \cdot i}\right)}{\ln(1+i)}. \quad (6)$$

We also calculated the costs related to the amount of supplied heat. Therefore, we evaluated the levelised costs of heat ($LCOH$) according to:

$$LCOH = \frac{TAC}{Q_{\text{tot}}}, \quad (7)$$

with the $TAC$, representing the annualised investment and the yearly operational costs, related to the annual supplied amount of heat $Q_{\text{tot}}$ to the separated district heating system.

The various conditions, such as a required heat pump system or the type of the conventional heating plant, are specific to the studied district heating system, its control strategy and its consumer characteristic. The district heating systems and their characteristics investigated as use-cases in this study are described in the next section.

## 3. Investigated Network Structures

We tested the developed framework for the separation of a district heating system with two different network structures that differ in shape and design approach of their pipe diameters. The different district heating systems are introduced, including consumer characteristics. Furthermore, we describe the new heat sources to be utilised and define the operating conditions for the new separated district heating system such as the newly established temperature level.

*3.1. FZJ Meshed Network Structure*

The district heating system of the Forschungszentrum Jülich (FZJ) in Germany formed the first use-case. The district heating system and its network structure have already been described in detail in [41]. The 34 km long district heating system supplies around 95 GWh of heat per year to the connected buildings on the campus and operates at a supply temperatures range of 95–132 °C depending on the actual outside temperature. The heat is generated by several CHP units and supported by additional HOB units. Since the studied network separations lead to heat supply reductions in the scale of the HOB heat supply, we can suppose that the reduced heat supply in the remaining network only affects the HOB supply. Therefore, only the resulting gas reductions relating to the reduced heat production were considered and not the decreased electricity production of the CHP units. For the case of reduced electricity production of the CHP units because of reduced operating hours and its effects on economic operation, we refer to [42].

Figure 3 symbolises the network structure of the FZJ district heating system. The network is presented in a simplified design [41]. The current heating plant is located in the south of the network, symbolised by a larger grey node and a red ring within. Furthermore, the new heat source, which should be utilised by network separation, is localised in the north of the network (see Figure 3).

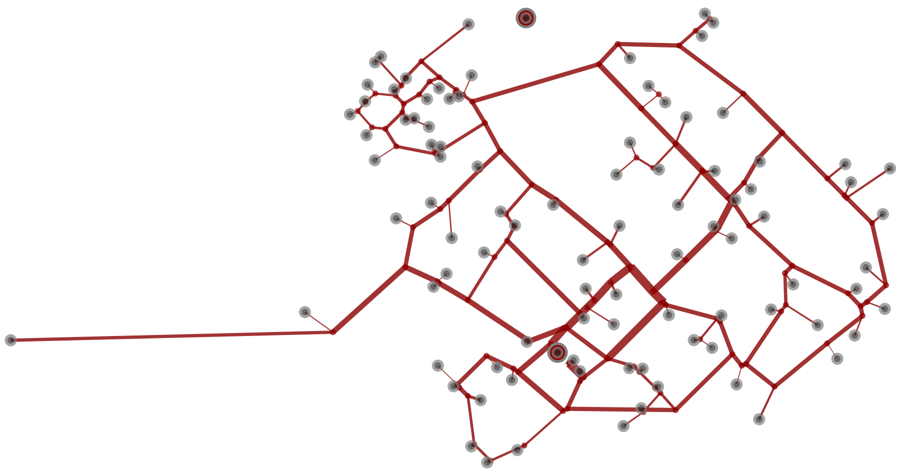


**Figure 3.** The meshed network structure of the district heating system at the FZJ: The various thicknesses of the edges symbolise the diameter of the installed pipes. Grey nodes represent the connected buildings and larger grey nodes with a red ring symbolise the heat sources.

Studying the FZJ district heating system for separation makes it possible to consider a real case study of an upcoming waste heat source. A new HPC facility is being built on the FZJ campus, which will emit a large amount of waste heat during operation [42]. An HPC facility thus represents a potential low-temperature waste heat source that could be used to supply a district heating system [43,44]. Therefore, we took the construction site of the HPC facility (see Figure 3) and the corresponding arising waste heat source on the FZJ campus as a real case study to apply our framework to the FZJ district heating network. The actual capacity of the new HPC has not yet been determined. However, to illustrate the framework in this study, we assumed a waste heat capacity of 5 MW, which is in the order of magnitude of the FZJ district heating system characteristics.

However, we could already deduce a waste heat temperature level of 40 °C from similar HPC cooling systems [43]. Since this temperature level is too low to supply the existing buildings on the campus, a central heat pump system increases the waste heat temperature to achieve a higher supply temperature in the separated district heating system. Depending on the set supply temperature level, the heat pump adds additional energy to the heat source and increase the available heat capacity.

As can be seen in Figure 3, the district heating network is constructed as a meshed network with several loops, which is mainly due to historical reasons. The campus has been continuously expanded over the past decades, resulting in a growing network. Therefore, the structure was not designed on an open field but grew over the years. In the context of historical expansion, the pipe diameters were also designed to retain some capacity for future network expansions.

Due to the expansion of the campus over decades, the building stock consists of buildings from several years of construction. Furthermore, the buildings are characterised by different types of usage, such as office buildings, workshops or laboratories. However, most heating systems in the buildings were initially designed for peak supply temperatures of 70 °C on the coldest days. The supply temperatures at the heating systems of the buildings are controlled by a heating curve, leading to frequently lower supply temperature requirements. Thus, temperatures lower than 70 °C will be sufficient for heat supply most of the year. To ensure a sufficient supply temperature at the buildings for the separated network, we controlled the supply temperature of the separated district heating system via a heating curve. Most times of the year, the heat pump increases the supply temperature at the heat source to 60 °C, which corresponds to the 4th generation or low-temperature district heating. On the coldest days of the year, the supply temperature was boosted up to 80 °C. With this implemented heating curve at the heat source, the separated district heating system should be able to distribute the required heat to the connected buildings. The heating curves of the heating systems in the buildings and for the set supply temperature at the heat source for the separated district heating system are shown in Figure 4.

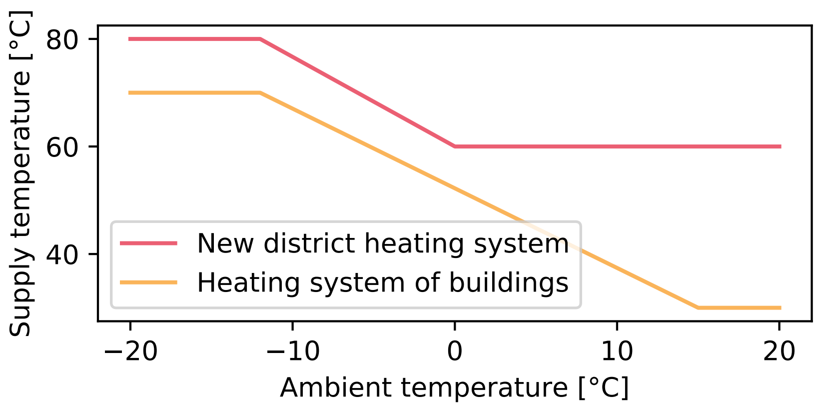



**Figure 4.** The heating curves of the heating systems in the connected buildings and of the supply temperature of the separated district heating system.

As described by Lund et al. [45], the temperature difference between supply and return should remain constant when the supply temperature is lowered in an existing district heating network to avoid an increase of the mass flow in the system. However, maintaining the temperature difference between supply and return is not always possible because not every connected building can reach such low return temperatures. Although we could not keep the temperature difference as in the existing district heating system, we set a lower design return temperature of 40 °C in the new separated district heating system that is practicable for the buildings.

For the district heating system at the FZJ, we had heat demand measurements of the connected buildings available. We used this measurement data from 2017 to investigate the possible network separation.

*3.2. Generic Spanning-Tree Network Structure*

We tested the framework with a second district heating system, which has a spanning-tree network structure. The network is generic designed in [46], where the operation of low-temperature district heating systems in typical residential areas is investigated. The typical residential areas are constructed based on typical building types, such as single-family or multi-family houses, different year of construction classes and their fractions in the German building stock. A generic network structure was designed to investigate the performance of low-temperature district heating systems in these constructed typical residential areas. Figure 5 shows this generically constructed spanning-tree network structure. This district heating network supplies heat to 100 connected buildings whose heat requirements depend on the investigated residential area and its included buildings.

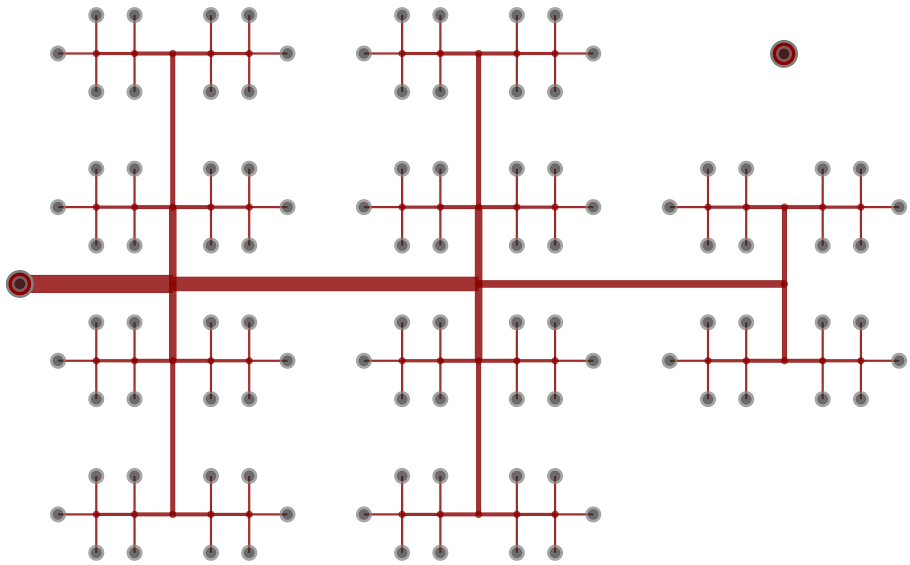


**Figure 5.** The spanning-tree network structure of the generic constructed district heating system: The various thicknesses of the edges symbolise the diameter of the installed pipes. Grey nodes represent the connected buildings and larger grey nodes with a red ring symbolise the heat sources.

We used one of these designed residential areas supplied by district heating to test our developed framework. Therefore, we used the generically designed district heating network in combination with the typical residential area where only multi-family houses from different years of construction classes are supplied. The heat demands of the connected buildings were simulated as was done in [46].

In contrast to [46], where a low-temperature network with decentralised heat pumps is investigated, we assumed a high-temperature district heating system in this study. Therefore, we considered the network structure and the heat demands of the connected buildings and designed the pipe diameters based on a high-temperature system with a supply temperature of 100 °C and a return temperature of 60 °C. We designed the diameters of the pipes based on the pressure gradient method as used in [47], setting a maximum design pressure loss of 200 Pa/m. Furthermore, we assumed that a natural gas-fired HOB supplied this high-temperature district heating system.

Since we investigated a generic district heating system, we had to set a generic present heat source that should be used for network separation. Therefore, we assumed a new HPC facility, as in the FZJ use-case, as an upcoming waste heat source in this generic use-case. However, due to a smaller network size and the lower heat demand, we assumed a smaller waste heat capacity than in the FZJ use-case of 1.2 MW. In Figure 5, the location of the new heat source is highlighted but not yet connected to the network structure. The available temperature level is still at 40 °C. For the temperature requirement of the connected buildings, we set a maximum temperature requirement of 70 °C during the coldest days, as this is sufficient for most types of heating systems [48]. The supply temperature was defined by heating curves. Thus, we also assumed a central heat pump at the new heat source and set the same supply temperatures for the new separated district heating system, as shown in Figure 4.

### 3.3. Further Constraints for Network Separation

To avoid separation scenarios too far away from the source or with too small heat demands, we had to set constraints for the minimal heat demand for network separation and the maximal distance between the identified community and the new heat source. As described in Section 2.1.3, these constraints are individual to the investigated systems and therefore were deduced from an assessment of different parameters in the scope of this study. The separated network should consume at least 5% of the available heat, otherwise the identified community was not further considered. Furthermore, the distance between the new heat source and the shortest path to the separated network should not exceed 5% of the total network length to avoid excessive investments. In addition, we deduced a constraint for the FZJ network that no pipes may be reassigned from the current network to the separated network within 400 m of the current heat source since the network pipes in this area were necessary for a faultless operation of the remaining district heating system. An alternative approach for setting these constraints is discussed in Section 5.

We also excluded one building in the north of the FZJ network because this building has special demands that a district heating system at a lower temperature level could not meet. In the generic network structure, we did not exclude areas or buildings since only similar heat demands occur in this district heating system, and the spanning-tree structure has no critical pipes that could not be separated. The assumed temperature levels, the available waste heat capacity, without additional energy of the heat pump system, and other constraints of both investigated district heating systems are summarised in Table 1.

**Table 1.** Summarised characteristics of the investigated district heating systems and the utilised heat sources.

| | FZJ | Generic |
|---|---|---|
| Supply temperature buildings [°C] | 30–70 | 30–70 |
| Supply temperature separated network [°C] | 60–80 | 60–80 |
| Available heat source capacity [MW] | 5 | 1.2 |
| Minimal demand of separated network [GWh] | 2.57 | 0.62 |
| Maximal distance for connection [m] | 684.22 | 164.47 |
| Excluded areas or buildings for separation | Yes | No |

## 4. Results

This section shows the results of the presented framework for network separation and the assessment of the different resulting separations, first for the meshed FZJ network and second for the spanning-tree generic network.

### 4.1. Separation of Meshed Network Structure

#### 4.1.1. Separation Scenarios of FZJ Network

As described in Section 2.1, we apply the Girvan–Newman algorithm to the network structure of the FZJ district heating network and test the resulting community identification for modularity. The community structure with the highest modularity of 0.8196 is presented in Figure 6. The nodes in a community are highlighted by specific colours and named with letters. The number of included buildings within that community is indicated in parentheses behind.

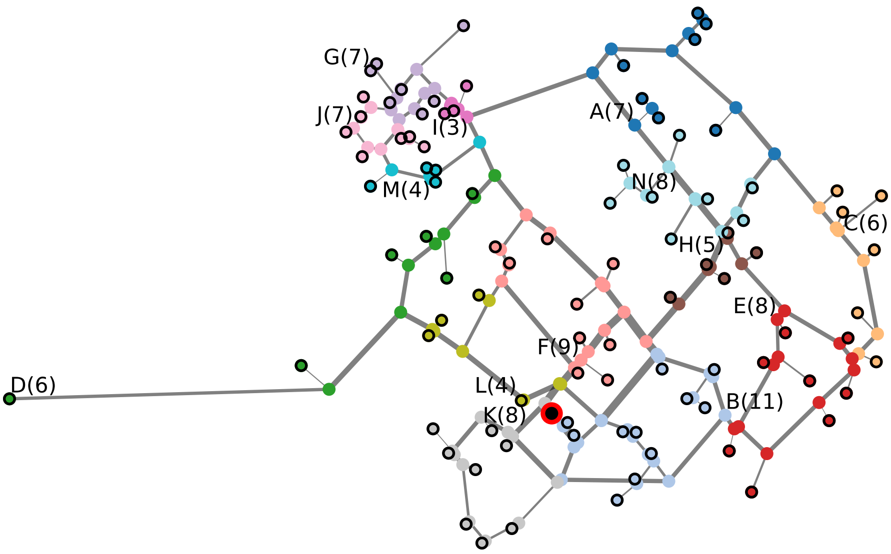



**Figure 6.** FZJ network structure with the identified communities highlighted and labelled; the corresponding number of included buildings is indicated in parentheses behind.

In Table 2, the resulting 14 communities of the network are summarised with the shortest distances to the heat source $s_{\min}$, the total number of included buildings and their summarised heat demands $Q_{\text{tot}}$, the maximal required heat supply $\dot{Q}_{\max}$ and the neighbouring communities. We already consider the simultaneous factors and estimated heat losses in the listed values of the total heat demands per year and the maximal heat supply.

**Table 2.** Identified communities in the network structure of the FZJ district heating system.

| Communities | $s_{\min}$ [m] | Included Buildings | $Q_{\text{tot}}$ [GWh] | $\dot{Q}_{\max}$ [kW] | Neighbouring Communities |
|---|---|---|---|---|---|
| *A* | 207.02 | 7 | 2.86 | 1464.68 | *N*, *C*, *I* |
| *B* | 911.99 | 11 | 6.13 | 2868.54 | *K*, *F*, *L*, *E* |
| *C* | 852.45 | 6 | 6.40 | 2467.90 | *A*, *E* |
| *D* | 375.34 | 6 | 5.72 | 2222.56 | *F*, *M*, *L* |
| *E* | 879.19 | 8 | 4.48 | 1971.42 | *H*, *C*, *B* |
| *F* | 485.84 | 9 | 10.71 | 3623.61 | *D*, *L*, *H*, *B* |
| *G* | 251.55 | 7 | 3.79 | 1427.32 | *J*, *I* |
| *H* | 664.93 | 5 | 2.80 | 1112.79 | *F*, *E*, *N* |
| *I* | 238.28 | 3 | 0.72 | 389.28 | *A*, *M*, *G* |
| *J* | 381.29 | 7 | 2.21 | 1051.57 | *G*, *M* |
| *K* | 1006.73 | 8 | 5.92 | 2702.12 | *L*, *B* |
| *L* | 703.30 | 4 | 1.38 | 561.81 | *F*, *B*, *D*, *K* |
| *M* | 298.32 | 4 | 1.63 | 633.51 | *J*, *D*, *I* |
| *N* | 472.31 | 8 | 14.65 | 4878.61 | *A*, *H* |

The next step is to identify which communities could be supplied by the new heat source and which could be combined to supply more buildings with the available heat source. With the capacity of the described HPC, including the additional heat pump energy and the maximal set distance to the separated network structure, communities *A* and *G* could be separated to establish an independent district heating system. The communities *I*, *J* and *M* are blanked out for a standalone separation because the aggregated heat demands of all buildings in these communities is less than the set minimal heat demand of 5% of the available heat (2.57 GWh). Furthermore, the communities *B*, *C*, *E* and *K* are not eligible for a direct connection because the distance between the heat source and the separated network is about the set maximal distance of 5% of the total network length (684 m). The communities *D*, *F*, *H*, *L* and *N* are not eligible for network separation because some included buildings and pipes in these communities belong to the marked areas that are essential for the original district heating system as specified in Section 3.3.

However, the framework combines some communities to form more extensive separated network structures. For example, community *A* can be extended by community *C*, which we previously marked as an unsuitable standalone network separation. However, as an extension of community *A*, community *C* could also be separated. Furthermore, also the summarised heat demands of communities *G*, *I* and *J* could also be met by the utilised waste heat source, although communities *I* and *J* were not considered a standalone network system. Table 3 summarises all resulting separation scenarios with their included communities and resulting heat demands. Not feasible network separations, such as the separation into three networks, are sorted out.

**Table 3.** Specified separation scenarios of the FZJ district heating system.

| Scenario | Communities | $Q_{tot}$ [GWh] | $\dot{Q}_{max}$ [kW] | $s_{min}$ [m] |
|---|---|---|---|---|
| 1 | *A* | 2.86 | 1464.68 | 207.02 |
| 2 | *A*, *C* | 9.26 | 3932.58 | 207.02 |
| 3 | *G* | 3.79 | 1427.35 | 251.55 |
| 4 | *G*, *I*, *J* | 6.72 | 2868.17 | 251.55 |
| 5 | *M*, *J* | 3.84 | 1685.08 | 381.29 |

Deduced from the resulting separation scenarios, the original district heating network is separated into different independent network structures. On the one hand, the remaining network supplied by the conventional heat source and still operating at high-temperatures, and on the other hand, the new network which is supplied by the upgraded waste heat. Figure 7 shows the network separation for scenario 2 as an example. The other separations of the FZJ district heating network are summarised in Appendix A.1.

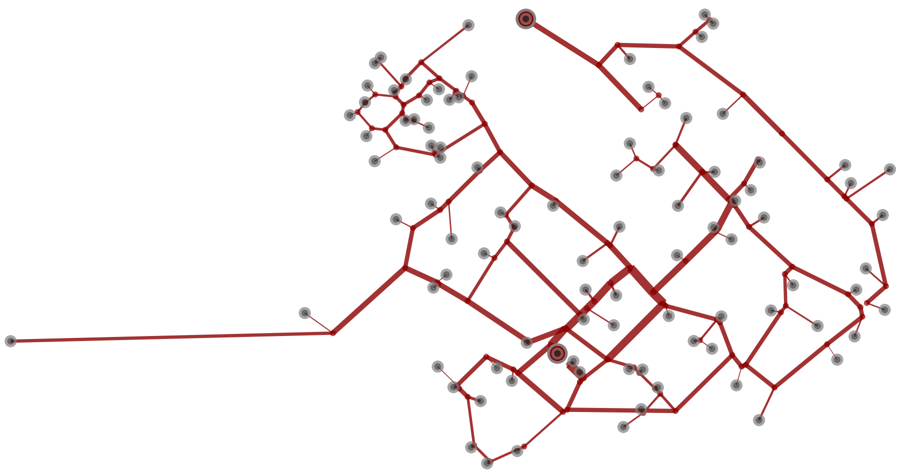


**Figure 7.** The resulting district heating systems of FZJ separation scenario 2.

### 4.1.2. Modified Heat Source Characteristics

To demonstrate the flexibility of the developed framework, we also show the resulting separation scenarios for a hypothetical different construction site and size of the HPC facility, resulting in an alternative heat source location with a changed amount of available heat. Therefore, we apply the framework to the same FZJ network structure but assume a different place of the waste heat source, randomly placed in a mesh of the network, with only half of the previously considered waste heat capacity (2.5 MW). As seen in Figure 8, the hypothetically adapted location of the waste heat source is now west of the current heating plant. The other set constraints, such as the maximal distance or the excluded areas around the conventional heat source, remain unchanged. Because the structure of the network does not change, the creation of separation scenarios bases on the same community detection as shown in Figure 6. The resulting separation scenarios for this adapted case are summarized in Table 4.

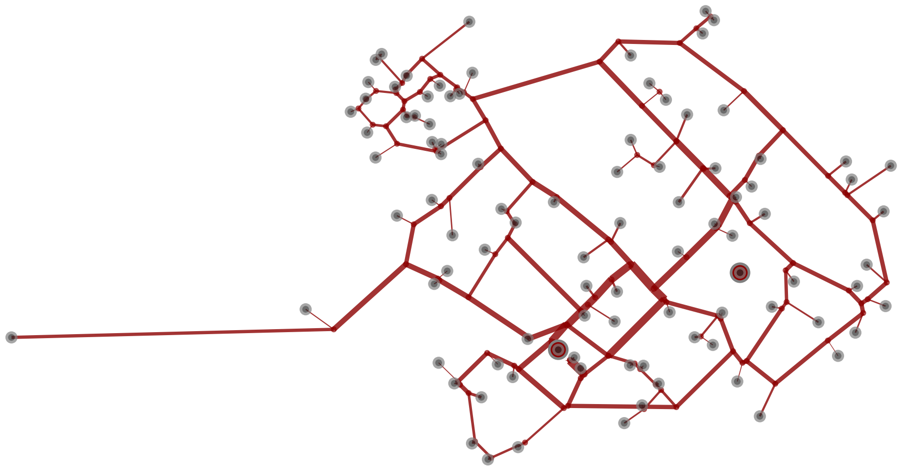


**Figure 8.** FZJ district heating system with hypothetical different construction site of the HPC facility and therefore different located waste heat source.

**Table 4.** Specified separation scenarios of the FZJ district heating system for different heat source site and less available amount of heat.

| Scenario | Communities | $Q_{tot}$ [GWh] | $\dot{Q}_{max}$ [kW] | $s_{min}$ [m] |
|---|---|---|---|---|
| 1 | *A* | 2.86 | 1464.68 | 394.3 |
| 2 | *C* | 6.40 | 2467.90 | 340.23 |
| 3 | *E* | 4.48 | 1971.42 | 109.66 |

The lower amount of waste heat causes that only single communities could form a separated district heating network without possible extensions of neighbouring communities, such as the extensions of community *C* by *A* or *E*. Other communities in the surrounding of the new HPC site are too close to the current heat plant and are part of the excluded areas, which were sorted out beforehand.

These separation results show that by simply adjusting the location and the available heat capacity, the framework always automatically reveals the possible separation scenarios depending on the network structure in the surrounding of the available heat source. Therefore, the framework could also be used for scenario investigation to evaluate different construction sites or to estimate the amount of heat that should be exploited for network separation. In the following, we demonstrate the evaluation results of the main investigated case with a waste heat capacity of 5 MW and the separation results shown in Table 3.

#### 4.1.3. Evaluation of FZJ Separation Scenarios

The simulation results show no additional bottlenecks in the remaining networks compared to the already existing ones in the original district heating system for all separation scenarios. However, new bottlenecks occur in the separated networks due to the higher mass flow rates. In scenarios 1, 2 and 4 only a few additional pipes will exceed the maximal set pressure loss (250 Pa/m) by values around 400 Pa/m but only during a few times of the year. In scenario 5, three critical pipes have pressure losses of 400–500 Pa/m during some times of the year. In Figure 9 the arising bottlenecks of separation scenarios 2 and 5 are highlighted. However, since these high pressure losses only occur at a few times a year, and especially the highest pressure losses results from the time step where all connected buildings have their highest heat demands, these bottlenecks are acceptable.

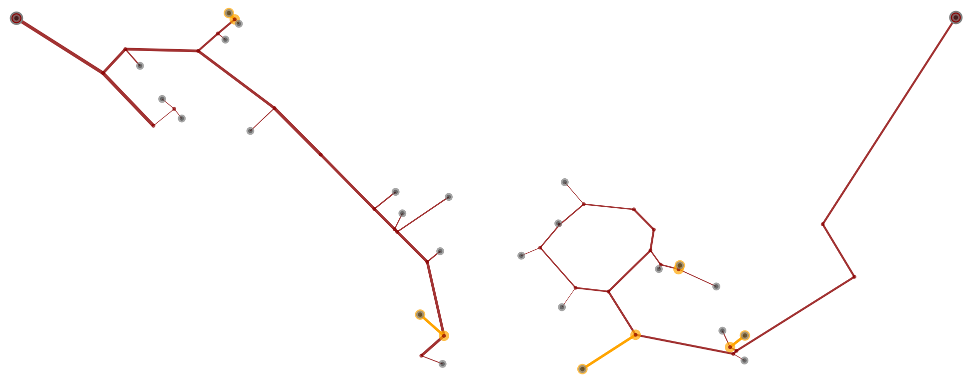



**Figure 9.** Bottlenecks (highlighted in orange) in the separated district heating networks of the FZJ use-case. (**a**) Separated network scenario 2; (**b**) Separated network scenario 5.

The bottlenecks in scenarios 3 and 4 were already part of the original network structure. However, low-temperature operation increases the specific pressure loss in these critical pipes to values around 800 Pa/m. Although this high specific pressure loss occurs in a relatively short pipe and results in only small absolute pressure losses, replacement of these critical pipes for low-temperature operation should be considered.

By examining sufficient temperature supply in the network structures, we identified one new critical building in the remaining network structure of scenario 4 that is supplied with too low temperatures at some periods of the year. In the separated district heating systems, three buildings in scenario 4 and two buildings in scenario 5 have supply temperatures that are sometimes too low. However, this minimal lack of comfort occurs for only a few hours per year in the summer. In summer, the heat demands are relatively low, which leads to small mass flow rates in some parts of the network and thus to high cooling rates of the fluid in the pipes. However, if realising the separation of a district heating system, these periods of slightly too low temperatures must be managed by local temperature boosting or installing storage systems to ensure the required heat supply.

The environmental impacts and the economic results of all investigated separation scenarios are summarised in Table 5.

Table 5 already provides an overview of the most promising separation scenarios. Scenario 2 is the option where most of the waste heat is used for the new separated district heating system. Due to the high amount of used waste heat, a large amount of gas consumption is reduced, leading to the highest possible $CO_2$ reduction of all scenarios. The highest gas reduction also leads to the highest *TAC*. However, the lowest *LCOH* are achieved in scenarios 3–5. In these scenarios with the lowest *LCOH*, the payback time of the project investment takes longest. Scenario 1 achieves the lowest payback time and the highest *LCOH* of all scenarios. From this first overview of scenario assessment, separation scenario 2 seems to be the most promising project to utilise the new heat source on the FZJ campus.

**Table 5.** Assessment results of all separation scenarios of the FZJ district heating system.

| | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 | Scenario 5 |
|---|---|---|---|---|---|
| Used heat [%] | 5.62 | 21.84 | 7.49 | 13.85 | 8.58 |
| $\Delta W_{\text{pump}}$ [MWh] | 0.25 | 13.85 | 3.07 | 5.64 | 4.34 |
| $\Delta W_{\text{el}}$ [MWh] | 240.07 | 940.70 | 332.34 | 614.73 | 378.95 |
| $\Delta Q_{\text{gas}}$ [MWh] | −6253.56 | −14676.13 | −4200.74 | −7444.17 | −4872.34 |
| $\Delta CO_2$ [tCO$_2$] | −1169.10 | −2605.61 | −722.71 | −1271.29 | −840.64 |
| $C_{inv}$ [Mio.EUR] | 1.30 | 3.12 | 1.36 | 2.32 | 1.66 |
| $C_{op}$ [TEUR/a] | 381.69 | 809.32 | 214.98 | 373.96 | 250.47 |
| $TAC$ [TEUR/a] | 315.38 | 650.39 | 145.66 | 255.35 | 165.95 |
| $LCOH$ [EUR/kWh] | 0.12 | 0.06 | 0.04 | 0.04 | 0.04 |
| $n_{crit}$ [a] | 3.65 | 4.15 | 7.11 | 6.98 | 7.48 |

### *4.2. Separation of Spanning-Tree Network Structure*

#### 4.2.1. Separation Scenarios of Generic Network

Applying the Girvan–Newman algorithm to the generic spanning-tree network structure yields the following community detection shown in Figure 10 with a modularity of 0.8404.

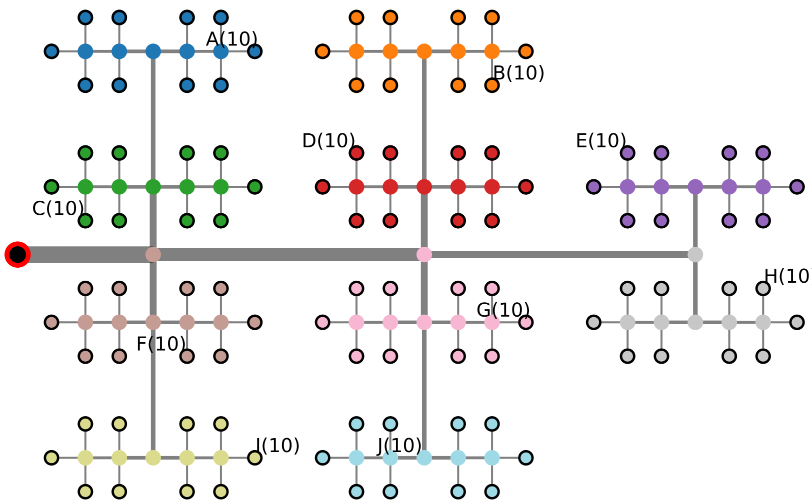



**Figure 10.** Generic network structure with the identified communities highlighted and labelled; the corresponding number of included buildings is indicated in parentheses behind.

In the spanning-tree network structure, the applied algorithm confirms the expected community structure that is already implied by the grouped building areas. However, not the coarser community detection where each branch from the main horizontal pipe forms a community has the highest modularity, but the less coarse community detection as displayed in Figure 10. Table 6 summarises the identified communities with their total $Q_{\text{tot}}$ and maximal $\dot{Q}_{\text{max}}$ heat demands, amount of included buildings, neighbouring communities, and the shortest connection distance to the new heat source $s_{\text{min}}$.

With the maximal distance to the new heat source of 164.5 m, the communities $B$, $D$, $E$ and $H$ can form an independent district heating system, separated from the original network. None of the identified communities has a heat demand less than the set minimal heat demand for possible separation. Furthermore, we do not define any excluded areas for separation in advance, so no areas were excluded for possible separation.

**Table 6.** Identified communities in the network structure of the generic district heating system.

| Communities | $s_{min}$ [m] | Included Buildings | $Q_{tot}$ [GWh] | $\dot{Q}_{max}$ [kW] | Neighbouring Communities |
|---|---|---|---|---|---|
| *A* | 440.85 | 10 | 1.49 | 670.39 | *C* |
| *B* | 104.79 | 10 | 1.49 | 670.39 | *D* |
| *C* | 370.86 | 10 | 1.30 | 639.11 | *F, A* |
| *D* | 125.91 | 10 | 1.17 | 618.37 | *G, B* |
| *E* | 69.81 | 10 | 1.17 | 618.37 | *H* |
| *F* | 335.87 | 10 | 1.13 | 656.25 | *I, G, C* |
| *G* | 195.9 | 10 | 1.09 | 692.43 | *J, F, H, D* |
| *H* | 104.8 | 10 | 1.09 | 692.00 | *G, E* |
| *I* | 440.85 | 10 | 1.08 | 690.30 | *F* |
| *J* | 300.88 | 10 | 1.08 | 690.30 | *G* |

The combination of communities *B* and *D* can form a larger separation scenario that the new heat source can still supply. However, if community *D* alone is separated from the original structure, community *B* will be cut off from the remaining network structure and could not be supplied by the conventional heat source. Therefore, community *D* could only be separated in combination with community *B*. Furthermore, communities *E* and *H* can be combined for a possible network separation. All resulting separation scenarios are summarised in Table 7.

**Table 7.** Specified separation scenarios of the generic district heating system.

| Scenario | Communities | $Q_{tot}$ [GWh] | $\dot{Q}_{max}$ [kW] | $s_{min}$ [m] |
|---|---|---|---|---|
| 1 | *B* | 1.49 | 670.39 | 104.79 |
| 2 | *B, D* | 2.66 | 1288.76 | 104.79 |
| 3 | *E* | 1.17 | 618.37 | 69.81 |
| 4 | *H* | 1.09 | 692.01 | 104.8 |
| 5 | *E, H* | 2.26 | 1310.37 | 69.81 |

Figure 11 shows the resulting district heating systems for the separation scenario 5 as an example. The first four possible separations of the generic district heating network are summarized in Appendix A.2.

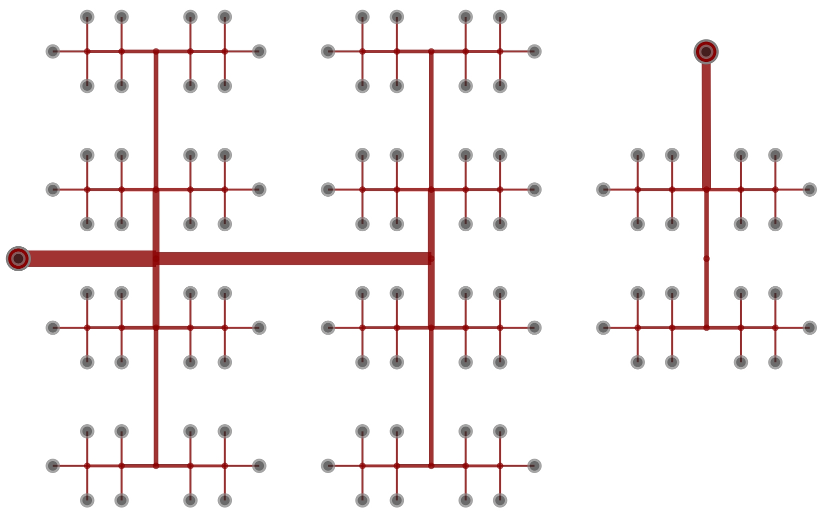
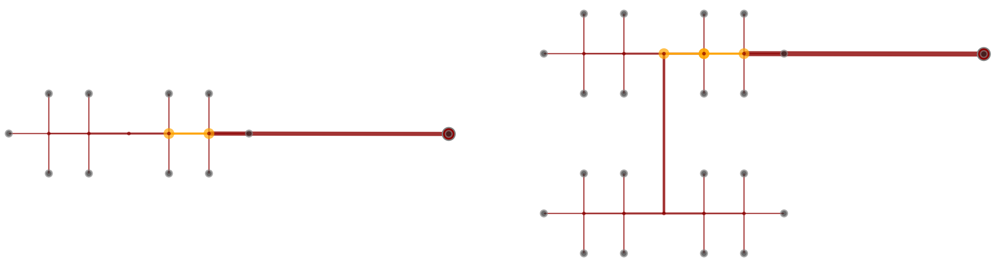


**Figure 11.** The resulting district heating systems of generic separation scenario 5.

4.2.2. Evaluation of Generic Separation Scenarios

The investigation of possible bottlenecks shows no bottlenecks in any remaining network structure since only isolated branches were separated from the original network structure. However, new bottlenecks occur in the separated network structures in scenarios 1 and 2. As can be seen in Figure 12, the connection pipe from the new heat source joins a side branch of the network in both scenarios. Therefore, the total amount of heat must pass this narrow pipe. Due to the small temperature differences and the resulting high mass flow rates, the main connecting pipe (see Figure 12) is a bottleneck during peak loads with high-pressure losses of around 1300 Pa/m for scenario 1 and even 6700 Pa/m for scenario 2. Therefore, these separation scenarios could not be implemented without additional changes to the network structure, such as replacement of this critical pipe. The related costs of such adaptions are not part of this investigation; however, the the additional expenditures are considered in the following comparison of all separation scenarios. Moreover, at the time step when all connected buildings have their highest heat demands, some additional pipes exceed the critical pressure loss of 250 Pa/m. However, since the pressure losses are only minimal above the critical value and arise only during one hypothetical time step, no additional adaptions are necessary.



(**a**) (**b**)

**Figure 12.** Bottlenecks (highlighted in orange) in the separated district heating networks of the generic use-case. (**a**) Separated network scenario 1; (**b**) Separated network scenario 2.

In scenarios 3, 4 and 5, the connections between the new heat source and the network structure are more advantageous because all delivered heat is integrated into a bifurcation of the network where also the original network structure distributes a lot of heat. Therefore, no bottlenecks occur in these scenarios.

The verification of sufficient heat supply in the remaining district heating system shows any critical buildings that cannot be supplied with the required heat. However, critical heat supply areas exist in the separated district heating systems of scenarios 4 and 5. The temperature difference between the primary and secondary side at these few buildings is less than 5 K and is present in less than 20 h per year. However, if such a separation scenario is realised, installing an additional storage system in the building or locally boosting the temperature could manage these few critical time steps.

Table 8 lists the economic results and the environmental effects of the separation scenarios of the generic district heating system.

All five separation scenarios achieve high waste heat shares up to 24%. Nevertheless, all scenarios have high payback times of up to 16 years, but the *LCOH* are relatively low compared to most FZJ scenarios. In separation scenario 2 and 5, most buildings are separated from the original district heating system, leading to the highest reduced gas consumption as the assumed gas boiler reduces its supplied amount of heat in the remaining network. Thus, the two major separation scenarios 2 and 5 achieve the highest possible $CO_2$ reductions. In addition, these scenarios also achieve the highest *TAC*, which emphasises the realisation of one of these separation scenarios from an environmental and economic point of view.

**Table 8.** Assessment results of all separation scenarios of the generic district heating system.

| | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 | Scenario 5 |
|---|---|---|---|---|---|
| Used heat [%] | 13.44 | 24.08 | 10.62 | 10.10 | 20.56 |
| $\Delta W_{\text{pump}}$ [MWh] | 1.47 | 4.15 | 0.93 | 0.95 | 2.18 |
| $\Delta W_{\text{el}}$ [MWh] | 146.86 | 264.65 | 115.94 | 109.01 | 224.32 |
| $\Delta Q_{\text{gas}}$ [MWh] | −1746.55 | −3137.59 | −1380.16 | −1290.71 | −2753.70 |
| $\Delta CO_2$ [$tCO_2$] | −297.31 | −533.79 | −234.98 | −219.5 | −471.39 |
| $C_{inv}$ [Mio.EUR] | 0.81 | 1.21 | 0.74 | 0.81 | 1.18 |
| $C_{op}$ [TEUR/a] | 86.36 | 156.23 | 68.11 | 63.30 | 138.67 |
| *TAC* [TEUR/a] | 45.14 | 94.25 | 30.17 | 22.08 | 78.60 |
| *LCOH* [EUR/kWh] | 0.03 | 0.03 | 0.03 | 0.02 | 0.03 |
| $n_{crit}$ [a] | 11.14 | 8.99 | 13.42 | 16.33 | 9.95 |

In contrast to high *TAC* and high $CO_2$ reductions, the *LCOH* is relatively high in the separation scenarios 2 and 5. However, scenario 2 may be difficult to realise due to the additional costs associated with the need to replace pipes to resolve the bottleneck problem mentioned before. Therefore, scenario 5 will be the most advantageous separation scenario for utilising the new waste heat source at this specific site.

## 5. Discussion

The presented framework for identifying possible network separations is a first step in implementing a new approach to integrate available heat sources in existing district heating systems. The Girvan–Newman algorithm reveals communities in the network structure that could be separated without the intervention of many pipes. However, the identification of possible separated district heating systems is currently based on the aggregated heat demands of the communities without considering any flexibility at the heat source. A more flexible matching between waste heat supply and the heat demands of the communities could be achieved by installing additional heat plants or using the already installed conventional heat source for peak loads. Thus, the new heat source could provide heat for larger areas. In addition, utilising multiple heat sources in the context of this framework would be helpful to apply it also in urban regions where several small waste heat sources could be used for one or more network separations.

Furthermore, the framework could be enhanced by optimisation approaches. Available heat sources will not always provide constant amount of heat, as it is the case with the HPC waste heat source under study. Fluctuating heat sources could also be integrated into the presented framework by considering additional thermal energy storage installations that compensate for the fluctuating heat supply. However, optimisation approaches could extend the presented framework for a more flexible and accurate matching of the available heat to the heat demands of the identified communities.

The avoidance of poor communities could be also improved by optimisation. Currently, the constraints to avoid poor community separation, such as maximal distance to the heat source or minimal heat demand, are set by assessments of different shares of network length or the available heat. An enhancement could be integrating the connection distance and the heat demand of the communities as variables in the mentioned optimisation problem. This approach would automatically sort out poor communities in advance that are too far away from the source or have too small heat demands, as they are either not economical or inefficient.

The feasibility check and the assessment of all separation scenarios reveal the most favourable options for the new heat source utilisation. Nevertheless, further investigations such as dynamic network simulations and more accurate economic calculations have to be carried out for the realisation of network separations.

The arising of bottlenecks in the separated district heating systems mainly depends on the existing network topology and the geographical location of the new heat source. If the shortest connection path joins a side branch of the original network structure, these narrow pipes, which are mainly used to supply one building, may cause bottlenecks in the new system and may need to be replaced. Such difficulty occurred in two separations scenarios of the generic network structure. Finding an alternative connection path, which would join the heat source to an existing pipe with a larger diameter, could avoid bottlenecks. This leads to an optimisation problem since either the additional costs for longer connection pipes are higher or the costs for the pipe replacement of bottlenecks.

## 6. Conclusions

This study presents a new framework to automatically identify network areas in a district heating system that could be separated to establish a new district heating system supplied by a present or newly constructed heat source. By applying the Girvan–Newman community detection algorithm to the district heating network structure, we are able to identify potential areas in the network structure for separation. In a second step, possible network separation scenarios are defined by matching the location and the available heat of the new heat source to the found communities. In the following, Modelica simulation models of all specified possible network separations are automatically constructed, simulated and evaluated to test the feasible district heating operation and to assess the environmental and economic benefits.

The presented framework for identifying, testing and evaluating possible network separations is tested with a meshed and a spanning-tree network and shows promising results for possible network separations. Moreover, we modify the site and heat source potential in one studied case to show the adaptability of the framework depending on the conditions of the investigated system. By analysing the simulation results of district heating operation, we can locate bottlenecks and critical buildings in the separated and the remaining district heating networks for all revealed separation scenarios. The assessment of the investigated network separations shows that especially large network separations lead to high emission reductions since the supply of the conventional heat plant decreases, which is often based on fossil fuels. All separation scenarios gain positive economic benefits if a cost free waste heat source is assumed where it is mainly the operation of the heat pump that leads to operational costs. As for the environmental benefits, the separations of large network sections also gain the highest economic benefits concerning the total annualised costs.

We test the method with a waste heat source that provides constant heat at a constant temperature level to meet the identified heat demands. However, in future work, the framework will be further developed by an optimisation approach to include the use of peak load plants or thermal energy storage to more flexibly match the supply of the heat source to the demands of the identified network areas.

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## Abbreviations

The following abbreviations are used in this manuscript:

| | |
|---|---|
| CHP | Combined Heat and Power |
| FZJ | Forschungszentrum Jülich |
| HP | Heat Pump |
| HPC | High Performance Computer |
| HOB | Heat Only Boiler |
| LCOH | Levelized Costs Of Heat |
| TAC | Total Annualised Costs |
| $A$ | Matrix of network structure (-) |
| $C$ | Costs (EUR) |
| $C$ | Community (-) |
| $i$ | Interest rate (%) |
| $k$ | Sum of weights of edges (-) |
| $m$ | Substitution variable ($m = \frac{1}{2}\sum A_{ij}$) |
| $n$ | Project Lifetime (a) |
| $P$ | Electric power (W) |
| $Q$ | Heat energy (Wh) |
| $\dot{Q}$ | Heat flow (W) |
| $s$ | Distance (m) |
| $T$ | Temperature (K) |
| $T$ | Time period (s) |
| $t$ | Time step (s) |
| $W$ | Electric energy (Wh) |
| $Z$ | Modularity (-) |
| $\Delta$ | Difference to status quo |
| $\delta$ | Kronecker delta |
| $\eta$ | Efficiency (-) |

## Appendix A

*Appendix A.1. Resulting District Heating Networks of FZJ Separation Scenarios*

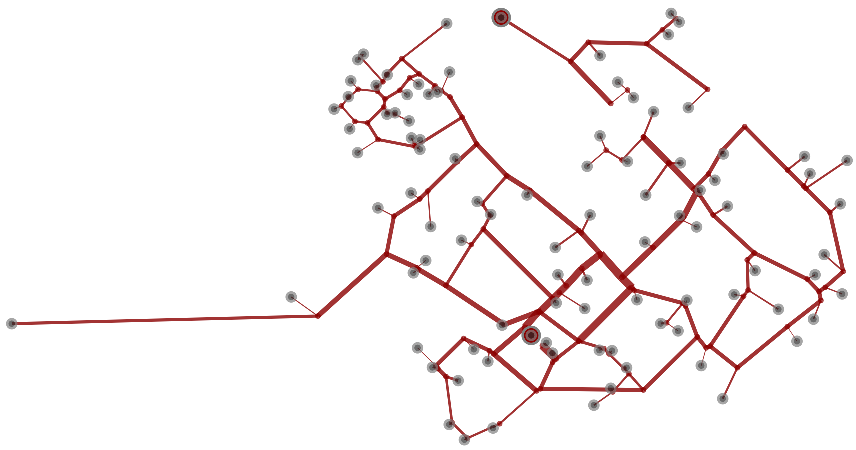

**Figure A1.** FZJ separation scenario 1.

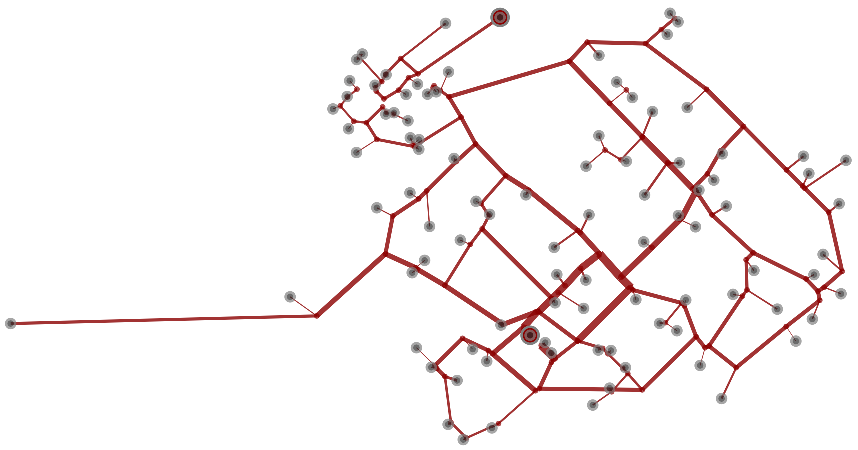

**Figure A2.** FZJ separation scenario 3.

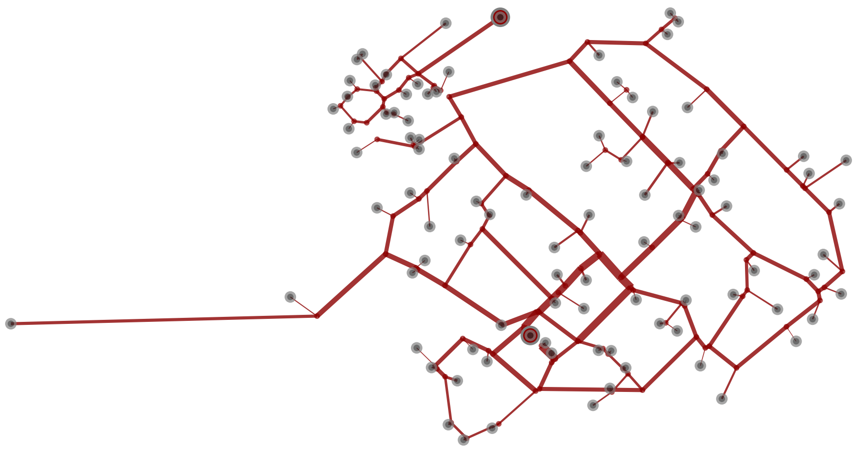

**Figure A3.** FZJ separation scenario 4.

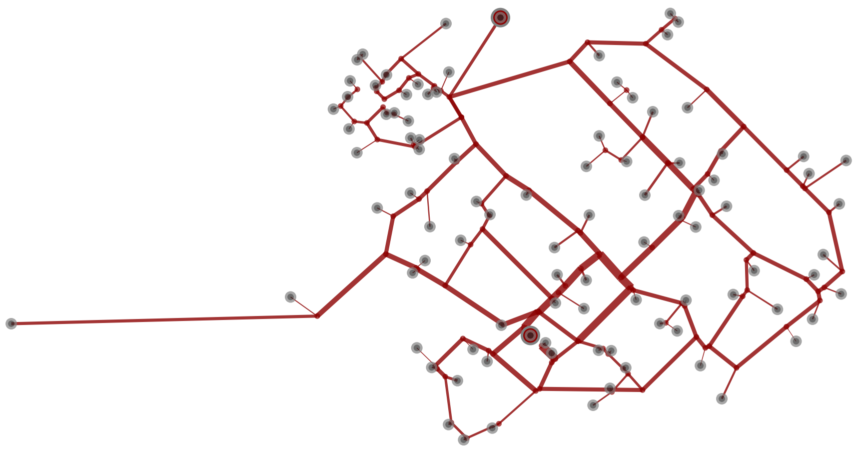

**Figure A4.** FZJ separation scenario 5.

*Appendix A.2. Resulting District Heating Networks of Generic Separation Scenarios*

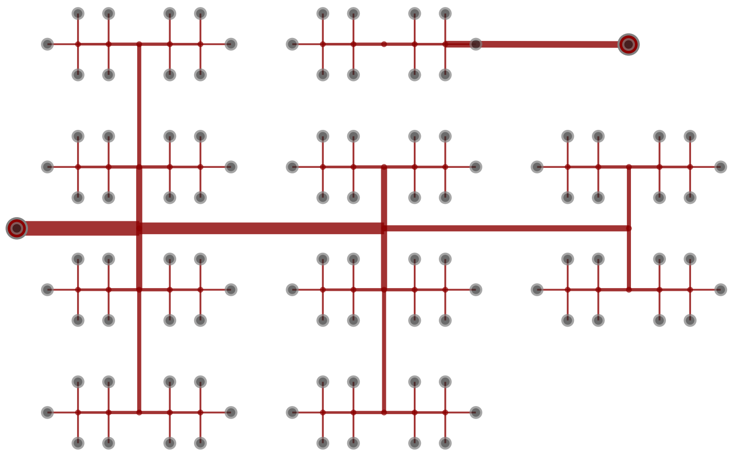

**Figure A5.** Generic separation scenario 1.

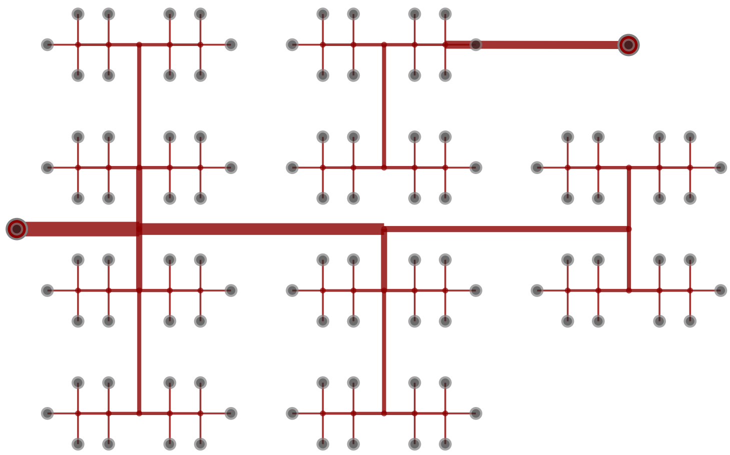

**Figure A6.** Generic separation scenario 2.

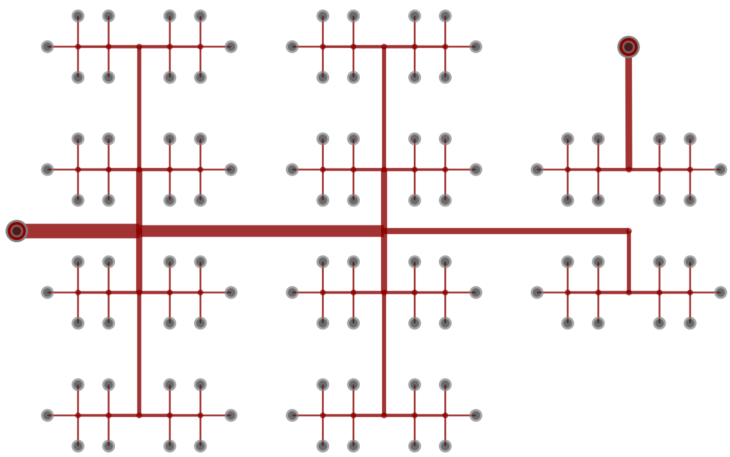

**Figure A7.** Generic separation scenario 3.

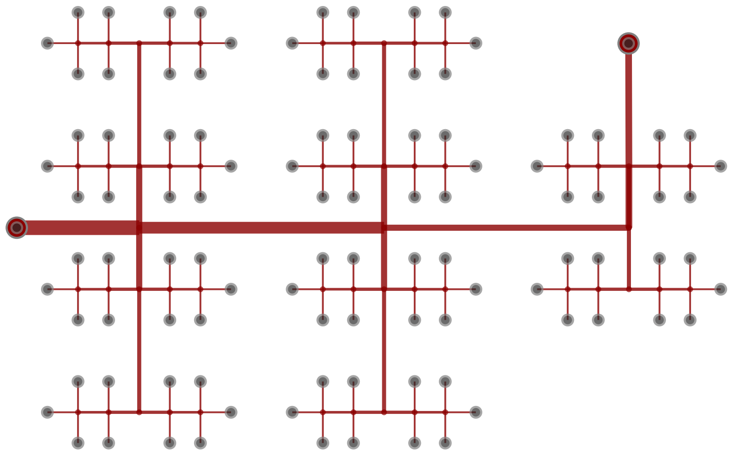

**Figure A8.** Generic separation scenario 4.

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