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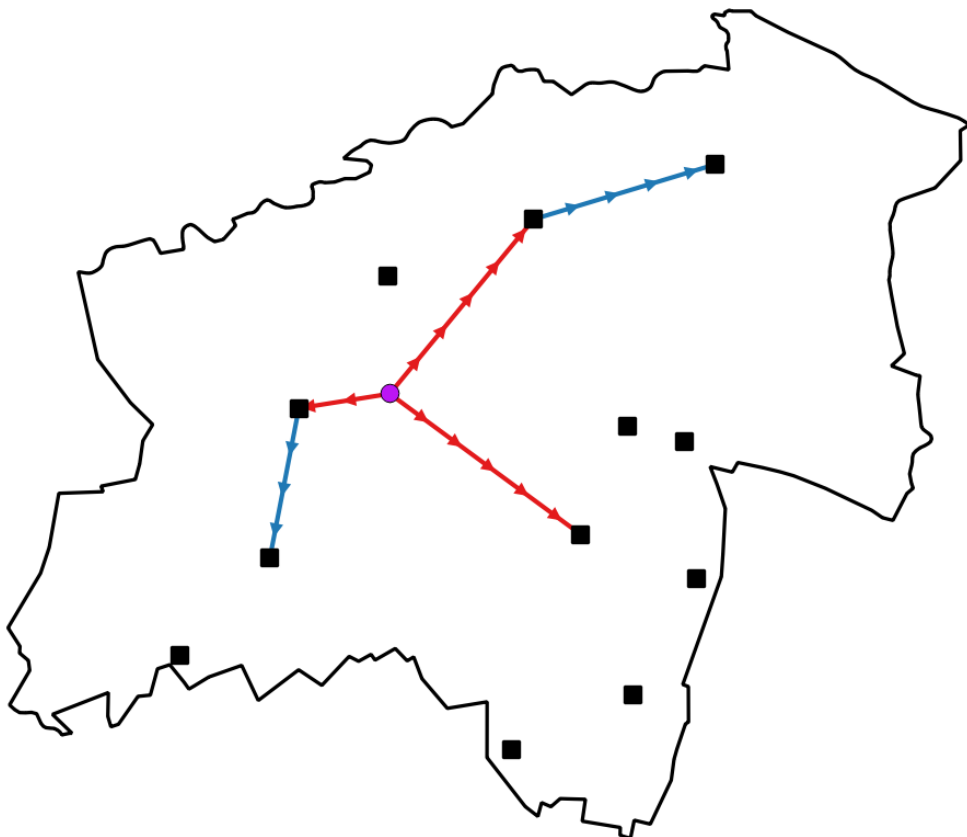
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Geothermal plants have been increasingly constructed in recent years to exploit the high geothermal energy potential in Germany in district heating networks at the municipal level. In order to use this potential economically, municipal planners need instruments for designing the district heating network to supply households with the geothermal heat. This paper presents a combinatorial mixed-integer linear optimisation model and a three-stage heuristic to determine the minimum costs for geothermal district heating systems in municipalities. The central innovations are the ability to optimise both the structure of the district heating network and the location of the district heating plant, the consideration of partial heat supply from district heating and the scalability to many larger municipalities. A comparison of optimisation and heuristic for three exemplary municipalities demonstrates the efficiency of the developed heuristic: the optimisation takes between 500% and 10,000,000% more time than the heuristic. The resulting deviations in the calculated total investment for the district heating from the results of the optimisation are in all cases below 5% and in 80% of cases below 0.3%. The efficiency of the heuristic is further demonstrated by the comparison with simpler heuristics like the Nearest-Neighbour-Heuristic. The latter is not only less efficient, it substantially overestimates the total costs by up to 80% in all cases with less than 100% heat coverage. Future work should focus on a more precise consideration of heat losses in the district heating network, as well as taking additional geological and topological conditions in the municipalities into account.

1. Introduction

The German energy sector is currently undergoing radical structural change due to ambitious national climate targets and supportive energy policy. This change is dominated by the expansion of renewable energy generation technologies, which are mainly exploited on a decentralised basis due to their characteristics (Wirth 2018). Thereby the energy system changes towards a more decentralised structure, which also applies to the owners and operators of energy plants (McKenna 2018). In Germany, private individuals increasingly invest in renewable energy systems or form energy cooperatives for this purpose. In fact, the majority of regenerative plants in Germany are owned and operated by private individuals, farmers and communities, which together are community energy in the wider sense (trend:research 2017).

The above-mentioned development has led to the generation of 33% of the electricity in Germany by renewable energies in 2017 (Statistisches Bundesamt 2017). In contrast, the proportion of renewable heat supply is around 13 % (UBA 2018). The installed capacity of renewable energies includes around 55 GW of wind energy (on- and offshore), 42 GW photovoltaic (PV) systems, about 7 GW of bioenergy and 39 MW of geothermal energy (BMW i 2017; UBA 2018). In comparison to the other renewable energies, relatively little electricity is generated by geothermal plants (GTPs) in Germany. Despite the fact that GTPs could make a major contribution to reducing greenhouse gas emissions, the installed capacity is still very low compared to the available resources (Agemar et al. 2018).

The currently (2017) installed 30 GTPs in Germany generate about 155 GWh of electricity and 1.3 TWh of heat annually, which is generally used for district heating (DH) applications (Weber et al. 2016; Agemar et al. 2018; UBA 2018). However, the German district heating networks (DHNs) are currently mainly supplied with heat by conventional gas and coal-fired plants (AGFW et al. 2018). Most of the heat is consumed in the residential sector, in which the market share of DH is 13.8% (Euroheat & Power 2017; AGFW et al. 2018). Between 2000 and 2017, DHNs are constantly being expanded and the consumption of DH in the residential sector increased by about 40% (AGFW 2017; AGFW et al. 2018).

The low emission of pollutants during operation of GTPs means that they could provide low-carbon heat for future DH systems. They could thereby contribute to higher levels of renewable heat supply, as is already achieved in some DHNs based on GTPs at the municipal level (Hechler & Bredel-Schürmann 2011). As the literature review in Section 2 shows, planning instruments are needed to support decision-making in the planning of municipal-level DHNs. The focus of this study is on the development of a novel method for designing a DH system based on geothermal heat in an arbitrary municipality. In comparison to existing work, this paper presents a generic approach for the simultaneous optimisation of DHN and DH plant

locations under local geographic conditions. Due to the high complexity of this combinatorial optimisation problem, an optimisation is not possible for a large number of settlements. Therefore, a heuristic is developed for the planning of the DHNs, whose efficiency is evaluated with the aid of the optimisation model. The location of the GTP as well as the DHN are designed depending on the location, heat demand and heat density of the individual settlements within a municipality. In the first stage of the three-stage heuristic, the integrated selection of the GTP location and the initial design of the DHN is performed. In the second stage, an algorithm is employed to optimise the design of the DHN. Based on the results, the optimum heat allocation to the settlements connected to the DHN is determined in the third stage. Beyond the development of this new approach, a way of using the results in a holistic energy system optimisation is addressed.

The paper is structured as follows. Section 2 provides an overview of the literature and clarifies the context of this paper. Section 3 then shows the methodology, before Section 4 presents and discusses the results. The paper concludes with a summary and conclusions in Section 5.

2. Literature review

This chapter highlights the novelty of the methodology developed in this study. First of all, Section 2.1 shows that previous energy system analyses with geothermal DH systems do not include a dimensioning of the DHNs. Afterwards, approaches for dimensioning DHNs are analysed and the differences to the evolved methods are identified (cf. Section 2.2). Section 2.3 concludes by clarifying the differences between the developed methods and typical combinatorial optimisation problems.

2.1. Energy system analyses with geothermal district heating

A few studies have already investigated energy systems in municipalities in which geothermal DH is used. Østergaard et al. (2010) investigate the feasibility of supplying the municipality of Aalborg in Denmark with renewable energy through a combination of low-temperature geothermal heat, wind power plants and biomass. The results of the simulations show that these technologies cannot cover the demand of Aalborg in every hour and that energy has to be imported instead. The study of Østergaard & Lund (2011) on Frederikshavn in Denmark, in which the city's energy demand should be 100% renewable, also takes deep geothermal energy into account as a heat generation plant with DHN. The simulations demonstrate that the operation of the GTP and the DHN reduces the energy imports of Frederikshavn. In the study of Sveinbjörnsson et al. (2017), the municipality of Sønderberg in Denmark is considered, which is aiming for zero net CO₂ emissions by 2029. Exactly as in Østergaard & Lund (2011), the GTP is combined with an absorption heat pump. The optimisations indicate that by supplementing combustion with modern energy conversion technologies, the climate targets can be achieved in a cost- and energy-efficient manner.

In the studies described above, the DHN already exists and is not further analysed. Besides, the location of the DH plant is not optimised in these studies but is specified manually beforehand. Some studies on DH in energy system analyses have been conducted in which DH is not based on geothermal energy such as Möller & Lund (2010). The authors examine the expansion of DH in a region in Denmark which is currently supplied with natural gas. The energy system of the region, however, is not optimised, but only analysed with the help of various scenarios. One conclusion is to replace natural gas with DH, especially in the vicinity of cities, and to increase the share of DH in the heat supply from 46% to 50%-70%. However, this paper indicates that the use of geothermal energy should be included in future analyses when considering DH. To the best of the authors' knowledge, energy system optimisations of entire municipalities in which the DHNs are designed simultaneously with other technologies have not been implemented so far. Section A.2 in the appendix shows how this could be accomplished in future energy system optimisations.

2.2. Algorithms for district heating design

Studies in which the design of DHNs is determined without the involvement of other energy technologies, by contrast, have been conducted with several different approaches. In general, however, these studies are based on a basic methodology, which is also the basis of our analysis, in which different nodes / buildings / settlements are connected by edges / pipelines. Table 1 summarises important characteristics of the studies discussed in this section. This paper distinguishes between bottom-up methods, in which the calculations are based on data of individual buildings and roads, and top-down approaches, which use e.g. heat and population densities.

The majority of studies dealing with the dimensioning and placement of DHNs are limited to DH pipelines within one urban area and do not consider the connection of several urban areas. Casisi et al. (2009), for example, determine the optimum layout of a DHN in conjunction with combined heat & power units in the city centre of Pordenone, Italy. The distances between the six considered buildings are specified beforehand. The location of the DH plant is not optimised here, but the authors note that this could lead to cost reductions. Damiana (2008) designs two district heating and cooling networks in the municipality of Udine in Italy with the help of an optimisation model. In designing the size and layout of the network, central and distributed generation of heating and cooling are combined and compared in consideration of the network costs. In the simulation model of Bratoev et al. (2017), the DHN with connections to the buildings is first generated on the basis of a road network. Afterwards the location of the DH plant can be selected, which is then connected to the DHN via the shortest distance. The algorithm requires an extensive building database, which must be collected in advance, for example through surveys. In Nielsen (2014), an algorithm is developed to economically

evaluate possible network expansions based on existing DHNs. This is done on the basis of cost calculations for heat production, distribution and transmission, based on geographical data. Although the model presented is transferable to Danish Regions, its application in German municipalities would fail due to the availability of data. To the authors' knowledge, shapefiles with building locations are not available for the whole of Germany. An extension of existing DHNs is also investigated by Delangle et al. (2017). In addition to DH, gas boilers, biomass boilers, heat pumps and heat storages are considered in a mixed-integer linear optimisation. The model can identify the optimal investment schedule for a DHN extension by a couple of buildings. The methodology can be applied to other DHNs, but in this case the existing DHN and the potential buildings to be connected have to be known. However, a planning instrument for German municipalities should focus more on the construction of new DHNs than on DHN expansion, as the share of DH in residential heating systems is less than 5% in over 85% of German municipalities (Statistisches Bundesamt 2014).

In Fazlollahi et al. (2014) and Unternährer et al. (2017), the DHN is dimensioned based on cluster analyses, in order to reduce the model complexity. The clustering of urban areas in Fazlollahi et al. (2014) results in combined urban districts whose energy demand and distribution costs of DH can be aggregated in order to subsequently optimise the DHN design. In Unternährer et al. (2017), the optimum design of the DHN is determined for each cluster. As in the present analysis, geothermal energy is used for DH. The authors highlight the economic value of geothermal energy for DH supply. However, memory restrictions occur during this analysis. Since only one settlement and not an entire municipality is analysed, this approach is not suitable to meet the objectives of our study.

Marty et al. (2018) highlight the relevance of a simultaneous optimisation of the DHN and the organic rankine cycle (ORC) as parts of a GTP. The optimisation of the DHN is integrated into a larger energy system optimisation, namely the optimisation of a GTP. However, no alternative energy generation technologies are taken into account in this energy system optimisation. Nevertheless, some differences to our study are apparent. The location of the DH plant is specified in the study and is not optimised. Furthermore, there is always a consumer who is connected, i.e. the construction of the DH plant is not decided but the DHN is built in any case. The heat demand of the consumers has to be completely covered and the consumers are not settlements in which additional networks for connections have to be included. No statement is made on the transferability of the model. Overall, however, it can be stated that the model in the study cannot be used for the purposes intended by our study. Dobersek & Goricanec (2009) determine the optimal tree branch path of a DHN in an urban area taking economy and functionality into account. The influence of construction cost, pump and electric energy cost on the type of optimal network is investigated. The locations of heat

source and consumers are defined in advance and the optimal network for a complete supply of all consumers has to be determined. The edges are also fixed in advance and cannot lead from each node to any other node. In the optimisation approach of DHNs in Bordin et al. (2016) the tree configuration of a network is determined starting from one heat supply plant. An existing network is assumed, which can be extended by potential pipelines and customers to maximise the net profit. For more complex analyses in future studies, the authors propose the use of heuristics to reduce computing times. Like the studies described above, the model from Bordin et al. (2016) is suitable for the individual planning of a DHN, but not as part of a larger energy system optimisation model of a municipality or region.

Table 1: Overview of studies about algorithms for DH design (R = residential sector, C = commercial sector, I = industrial sector, BU = bottom-up method, TD = top-down method).

Study	Method	Network building or expansion?	Determination of plant location?	Sector	Region	Easily transferable?
Damiana 2008	Optimisation model (BU)	Building	No	R, C, I	Urban area (Italy)	No
Casisi et al. 2009	Optimisation model (BU)	Building	No	C	Urban area (Italy)	No
Dobersek & Goricanec 2009	Optimisation model (BU)	Building	No	n.a.	Urban area	No
Fazlollahi et al. 2014	Cluster analysis and optimisation model (TD)	Building	No	n.a.	Urban area	No
Nielsen 2014	Heuristic (BU)	Expansion	No	n.a.	Arbitrary Danish municipality	Yes
Bordin et al. 2016	Optimisation model (BU)	Expansion	No	R, C	Urban area	No
Bratoev et al. 2017	Heuristic (BU)	Building	No	R, C	Urban area	No
Delangle et al. 2017	Optimisation model (BU)	Expansion	No	n.a.	Urban area	No
Unternährer et al. 2017	Cluster analysis and graph theory (TD)	Building	No	n.a.	Urban areas (Switzerland)	No
Marty et al. 2018	Optimisation model (BU)	Building	No	n.a.	n.a.	No
Our Study	Optimisation model and heuristic (TD)	Building	Yes	R	Arbitrary German municipality	Yes

In summary, the studies analysed use optimisation models and heuristics respectively (cf. Table 1). In articles about optimisation models, the choice of heuristics is suggested for more complex studies, but these two approaches are not compared in any of the studies. In addition,

none of the studies in which the networks are newly built is suitable for use in entire municipalities, but only for planning DHNs in urban areas. Furthermore, the studies cannot easily be applied to arbitrary municipalities in Germany. All these points are addressed with the approaches in the present article.

2.3. Combinatorial optimisation of networks

Most, if not all of the studies in the previous section use the methodology of combinatorial optimisation. As particularly evident in the studies by Dobersek & Goricanec (2009) and Bordin et al. (2016), the optimisation of network design in DH systems falls within the scope of minimum spanning tree (MST) problems. Therefore, papers on MST problems are analysed in the following in order to draw conclusions for DHN optimisations.

Smith & Walters (2000) describe an evolutionary approach based on genetic algorithms to find the optimal trees in undirected water, gas or material networks. Based on the construction and operating costs, a network tree is identified that is close to the optimum. In order to be able to execute the genetic algorithm, however, starting solutions must first be identified. Blanco et al. (2017) extend the MST problem so that the nodes are not points but belong to regions with a certain geometry to reflect uncertainty of the location of a node. Efficient algorithms and formulations of the problem have been implemented by the authors to solve the problem in a reasonable time. The methodology with the uncertain locations of the heat consumers could also be relevant for DH designing models (cf. Section 4.4). Fernández et al. (2017) focus on multiobjective spanning trees and aggregate the vector of the objective values. Formulations of the problem are developed which reduce the number of decision variables and thus the time needed to solve the problem.

Gao & Jia (2017), Salgueiro et al. (2017) and Gouveia et al. (2014) investigate another form of the MST, the degree-constrained minimum spanning tree (DCMST). The problem formulation of the DCMST contains additional restrictions regarding the degree of the nodes, i.e. how many edges are connected to a node. This restriction is not meaningful for the DHNs considered in our study, as an unlimited number of pipelines should be allowed to enter and leave the nodes. In addition, there is no need to limit the number of end nodes / leaves as done in Gouveia & Simonetti (2017). In this study, they develop a competitive model for the max-leaves problem. Cerrone et al. (2014) show in their paper that a spanning tree with a minimum number of leaves is better suited for minimising the number of light-splitting devices required in optical networks than two other MST problems. In Marín (2015), the MST problem is adjusted to minimise the number of branches, i.e. nodes with a degree greater than two. As in our study, a multi-stage heuristic is being developed for this problem. However, the limitation of the number of branches should not apply to DH systems either.

The approach for DHNs in our study differs from the MST problems described above in the following points:

- Not every node has to be connected (cf. Eq. 8-10 in Section 3.2).
- Not only the edges, but also the nodes have weights (cf. Eq. 3 in Section 3.2).
- Edges go from every node to all other nodes (cf. Eq. 2 in Section 3.2).
- A decision must be made "to which percentage" a node is connected (cf. Eq. 3, 5 and 11 in Section 3.2).
- Instead of one starting point / source, there is an arbitrary number of sources, of which one must be selected (cf. Section 3.1 and Eq. 6 in Section 3.2).

The aim of this paper is not only to provide a unique optimisation problem / heuristic for the planning of DHNs in municipalities, but also to solve the problem in a reasonable time. Furthermore, the method presented in the following section should be applicable to every municipality in Germany.

3. Methodology

The distance to the heat consumers is crucial for the costs of using heat in DHNs. Therefore, an optimisation model as well as a heuristic for the designing of DHNs and the placement of the DH plant is developed in this study. In the models, the location of the GTP and the connection of the settlements by a DHN are determined for an arbitrary municipality considering the minimisation of the investment for the DHN. Possible locations for the GTP are specified in advance, as the following Section 3.1 shows, which describes the determination of input data and the most important assumptions. The optimisation model for determining the optimal DH system is presented in Section 3.2 and the heuristic in 3.3.

3.1. Input data generation and assumptions

The optimisation model and the heuristic are demonstrated using the German municipality "Groß Kreuz", which is shown in Figure 1. The figure illustrates the possible locations for placing the GTP as purple circles and the pink areas are CORINE Land Cover (CLC) settlement areas from EEA (2016). The number of possible locations of the GTP can be specified manually via the distances between the purple circles. The locations were set so that 35 locations are between the minimum and maximum longitude coordinates and/or latitude coordinates. In Groß Kreuz this results in 497 possible locations i.e. 5 locations per km². Section 4.3.2 shows that this number is sufficient, as a further increase does not significantly affect the results. The shapefiles of these CLC areas are provided by the Federal Office of Cartography and Geodesy (Lenk et al. 2017). Some of the purple circles are close to the settlement areas, since GTPs do not have to keep a minimum distance to settlements as long as measurements are taken to assess vibrations according to DIN 4150-3 (HLUG 2011). Using

OpenStreetMap, inadmissible areas such as settlements, water areas, forests, etc. were excluded as locations for the GTP¹. The settlements marked in pink differ in terms of their heat demand and building density. The most important assumptions include the specific costs c_p for pipelines outside the settlements, which are estimated to be 200 €/m (C.A.R.M.E.N. e.V 2012; Pfnür et al. 2016). The relatively low value of 200 €/m is supposed to reflect the receipt of a subsidy in the context of the Combined Heat and Power Act (KWKG) amounting to 100 €/m of DHN built (BMJV 2018). However, the 200 €/m are above the 160 €/m in the geothermal project Grünwald (Erdwärme Grünwald GmbH 2013). The DH substations are assumed with a reference size of 250 kW (Connolly et al. 2014; Le Truong et al. 2015). If the heat demand in a settlement exceeds 250 kW, more than one substation has to be built. According to Connolly et al. (2014) and Le Truong et al. (2015), the costs for one substation c_s are assumed to be 4000 € and 70 €/kW, i.e. 21,500 € for 250 kW. The pipeline costs within the settlements are estimated using the methodology of Persson & Werner (2011).

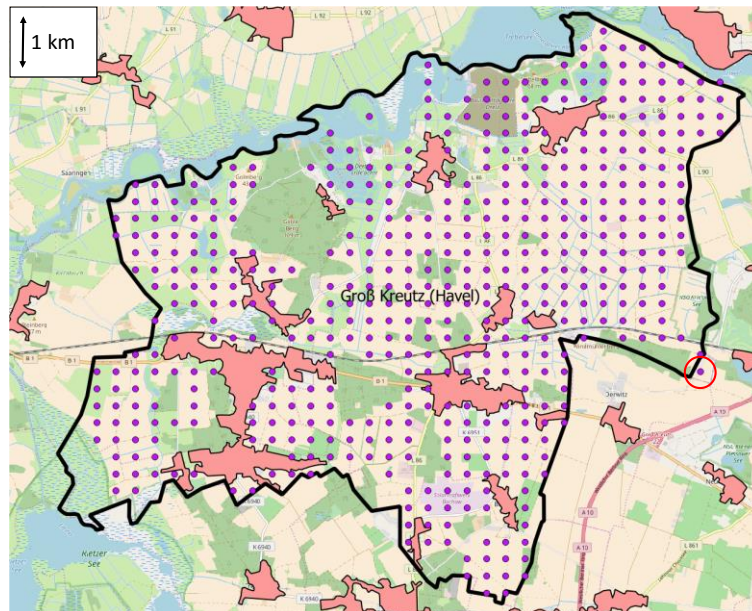


Figure 1: Possible locations (purple circles) for building the GTP in the municipality Groß Kreuz (Havel). The background map in this and the following figures is from OpenStreetMap contributors (2018).

Parameters for all German settlements required for this study are taken from Weinand et al. (2018a), including the heat demands, living spaces, population densities, coordinates of the centroids etc. This also includes the shares of existing DH supplies in the total heat supply,

¹ The red encirclement at the right of Figure 1 represents a possible error in the placement of the purple circles. The error occurs due to the fact that OpenStreetMap uses slightly different municipal boundaries, which differ from the municipal boundaries of the shapefiles from the Federal Office of Cartography and Geodesy used here to illustrate the municipality. These possible errors can be neglected as they only occur at the municipal boundaries and are rather unlikely to be chosen as the location for the GTP due to the large distance to the settlements.

which are subtracted from the heat demand of the settlements in the optimisation as well as in the heuristic. This is intended to prevent district heating networks from being built where networks already exist. These data for all German settlements and the heuristic are made available as supplementary material. In addition, the necessary input data for the municipality Groß Kreutz are provided as an example. Section A.2 in the Appendix additionally explains and discusses in which way the results of the heuristic could be used in a holistic energy system optimisation of a municipality.

In the following section, variables are marked in bold letters. A nomenclature of variables and parameters can be found in Section A.1 of the appendix.

3.2. District heating system optimisation

The combinatorial optimisation model for the cost-optimised placement of the GTP as well as the determination of the optimal DHN minimises the total costs C_{total} . These costs consist of the costs for the DH pipelines in and outside the settlements, $C_{pipe,in}$ and $C_{pipe,out}$, as well as the DH substations C_{sub} according to Eq. 1.

$$\min C_{total} = C_{pipe,out} + C_{pipe,in} + C_{sub} \quad 1$$

$$C_{pipe,out} = \left(\sum_{l=1}^m \sum_{i=1}^n x_{G,l,i} \cdot l_{G,i,l} + \sum_{i=1}^n \sum_{j=1}^n x_{S,i,j} \cdot l_{S,i,j} \right) \cdot c_p \quad 2$$

$$C_{pipe,in} = \sum_{i=1}^n \left(HDC_i \cdot \sum_{t=1}^{T=8760} \dot{Q}_{i,t} \cdot p_i \right) \quad 3$$

$$C_{sub} = \sum_{i=1}^n (N_{S,i} \cdot p_i) \cdot c_s \quad 4$$

$$\dot{Q}_{G,t} - \sum_{i=1}^n \dot{Q}_{i,t} \cdot p_i \leq 0 \quad \forall t = 1, 2, \dots, 8760 \quad 5$$

$$\sum_{l=1}^m b_{GL,l} = 1 \quad 6$$

$$\sum_{i=1}^n x_{G,l,i} \leq b_{GL,l} \cdot n \quad \forall l = 1, \dots, m \quad 7$$

$$\mathbf{b}_{GS,i,1} \cdot 1 \leq \sum_{l=1}^m \mathbf{x}_{G,l,i} \quad \forall i = 1, \dots, n \quad 8$$

$$\mathbf{b}_{GS,i,2} \cdot 2 \leq \sum_{l=1}^m \mathbf{x}_{G,l,j} + \mathbf{x}_{S,j,i} \quad \forall i, j = 1, \dots, n \quad 9$$

⋮
⋮
⋮

$$\mathbf{b}_{GS,i,\sum_{a=1}^n n!/(n-a)!} \cdot n \leq \sum_{l=1}^m \mathbf{x}_{G,l,j} + \mathbf{x}_{S,j,k} + \mathbf{x}_{S,k,o} + \dots + \mathbf{x}_{S,z,i} \quad \forall i, j, k, o, \dots, z = 1, \dots, n \quad 10$$

$$\mathbf{p}_i \leq \mathbf{b}_{GS,i,1} + \mathbf{b}_{GS,i,2} + \dots + \mathbf{b}_{GS,i,\sum_{a=1}^n n!/(n-a)!} \quad \forall i = 1, \dots, n \quad 11$$

The costs for the pipelines outside the settlements $C_{\text{pipe,out}}$ are determined using the vectorised geodetic distances $l_{G,i,l}$ between the GTP at location l and a settlement area i as well as the $l_{S,i,j}$ between two settlement areas i and j (cf. Eq. 2). The binary variables x_G and x_S are used to decide which pipelines should be constructed. Thereby m possible locations of the GTP and n different settlements are given. One of the m different geothermal locations has to be selected via the binary variable b_{GL} (cf. Eq. 6). The variable b_{GL} then also restricts the possible pipelines that can be built using Eq. 7. This ensures that only connections starting from the chosen geothermal location can be selected.

The costs for the DH pipelines inside the settlements $C_{\text{pipe,in}}$ are determined with the help of the specific heat distribution costs HDC_i and the heat supply \dot{Q} per hour t in a settlement i (cf. Eq. 3). The variable p_i gives an indication of which proportion of the settlement is supplied with heat and therefore takes values between 0 and 1. The heat distribution cost is calculated on the basis of Persson & Werner (2011), depending on the population and building density as well as the specific heat demand. The settlements have to consume the entire heat \dot{Q}_G of the GTP (cf. Eq. 5). This amount of heat should be adjusted in advance according to the specific use case or the geothermal potential available in the municipality. Figure 2 qualitatively illustrates the influence of p on the proportion of heat demand to be covered in a certain settlement. The variable p thus depends on the highest heat demand that occurs in a settlement. For example, the red area and the two areas of heat demand shown below are covered, if $p = 1$ is selected. The GTP, if operated during the whole year, would generate surplus energy in summer. For this study, the use of the surplus energy is not relevant, however, electricity could be generated in a GTP in this time period.

For each settlement at least one DH substation is required to connect the heating system of the buildings with the DHN. The costs for one substation c_s are multiplied by the number of substations N_s and the proportion of the settlement supplied with heat to determine the costs for DH substations C_{sub} in Eq. 4.

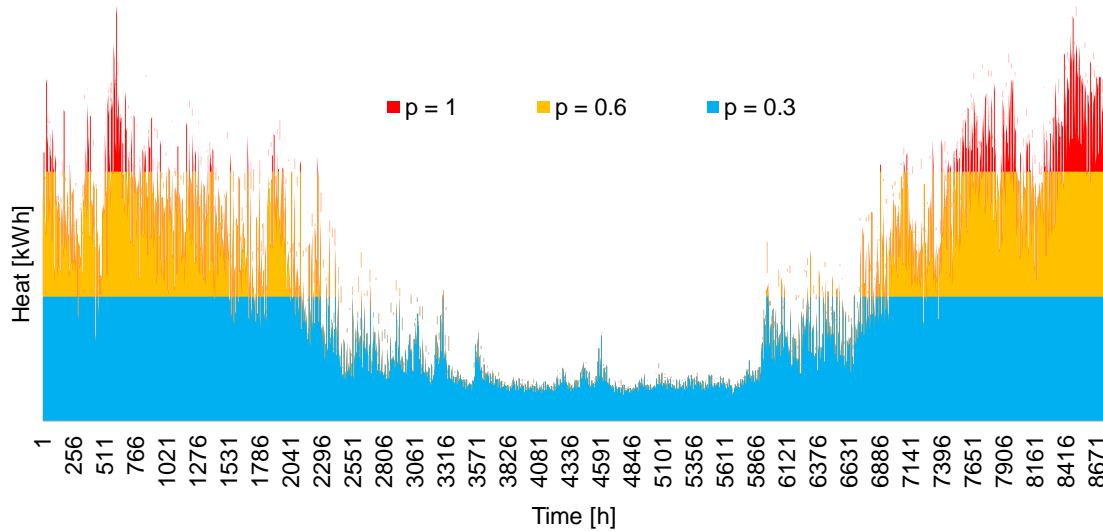


Figure 2: Influence of the variable p on the heat demand covered by the DH plant in a settlement.

A subtour is the term used when two or more coherent graphs are created as a solution instead of one coherent graph. In order to prevent subtours, it must be ensured that each sink / settlement is connected with the source / GTP via a coherent path. For this purpose, equations are set up for each possible path from the source to the sink (cf. Eq. 8-10). The binary variable b_{GS} is used to decide by which path a certain settlement can be reached. This path must begin at the GTP. For a certain settlement, several paths could be selected, but this would lead to higher costs according to Eq.2. For example, in Eq.8 the pipeline would lead directly from the GTP to a settlement, while in Eq.10 the pipeline would lead across all other settlements. Thereby the number of restrictions depends on the number of settlements and can be calculated via $\sum_{a=1}^n n!/(n-a)!$. The number of equations therefore increases exponentially with the number of settlement areas in a municipality. Eq. 11 has to be included so that no settlement can be supplied with heat that is not connected to the GTP via DH pipelines.

3.3. Heuristic for designing district heating systems

The optimisation problem described above can only be solved for municipalities with less than eight settlements due to calculation time limitations (cf. Section 4.1). Even the building of equations is not possible for municipalities with more than ten settlements due to computational constraints on the used computers (cf. Section 4.1). In order to solve the problem for larger municipalities, a heuristic has been developed in addition to the optimisation problem. The heuristic is similar to algorithms for solving the combinatorial optimisation problem of the minimum spanning tree. In contrast to the general minimum spanning tree problem the nodes to be connected are not previously fixed and the weights of the edges can change in each iteration. The heuristic is executed for each possible GTP location, which are determined in advance (cf. Figure 1). Before starting the heuristic, the percentage of the municipality's heat demand to be covered by the GTP must be specified (cf. Figure 4). After determining the

distance matrices, a loop is performed for all GTP locations, therefore the boxes in Figure 4 are shown nested. The heuristic then selects a connection from the geothermal system to one of the settlements in the municipality. In the example of the municipality Groß Kreutz a choice must be made between 12 settlements. The decision is made on the basis of the investment for the DH system per supplied amount of heat. If only costs for the pipelines would be considered, the nearest and most densely built-up areas would be selected. This would lead to high costs, as in most cases more settlements would have to be connected with DH pipelines, since the first settlements that would be connected might not occur in the optimal solution. Subsequently, the hourly heat demand of the settlement is subtracted from the heat supply of the GTP. The next DH connection is selected if the GTP still has heat available and there is still demand in the settlements. All settlements to which a connection already exists are now included as possible heat sources. This means that in each iteration there is an additional heat source that can be connected to the other settlements.

The first stage of the heuristic is completed as soon as the heat supply of the geothermal system is exhausted and is a modified form of the algorithm from Weinand et al. (2018a). The upper part of Figure 3 shows the result after the first stage for the case that 100% of the heat demand is covered in Groß Kreutz. The red lines represent the DH pipelines originating from the GTP, the blue ones those originating from a settlement and the GTP is illustrated as a purple circle. The upper part of the figure shows, above all in the part encircled in red, that the shortest connections are not always used. This is due to the iterative approach of the heuristic, whereby one connection is chosen in each step. In previous iterations, connections could have been selected that would not have been selected if all connected settlements had been known beforehand. Therefore, the heuristic is extended by a second stage with another target criterion: the costs for the connecting lines outside the settlements. However, the selection of settlement areas in this second stage is limited to those settlements that were connected in the previous stage. This leads to a more economical connection, as shown in the lower part of Figure 3.

Another problem can be caused by the iterative approach. In case the heat demand is not met to 100%, the last selected settlement will only be partly supplied with heat ($p < 1$). However, this last connected settlement could have a higher heat density than another settlement connected to the DHN. Then it would be reasonable to supply the last selected settlement with more heat and proportionally supply the settlement with the lowest heat density and the highest specific heat distribution costs HDC respectively. Therefore, the heat supply is reassigned to all selected settlements on the basis of the HDC in the third stage of the heuristic. Finally, the DH connections and the associated costs and CO₂ abatements per year

are given as output. For calculating the CO₂ abatement, the actual heating technologies in the various settlements were determined in Weinand et al. (2018a).

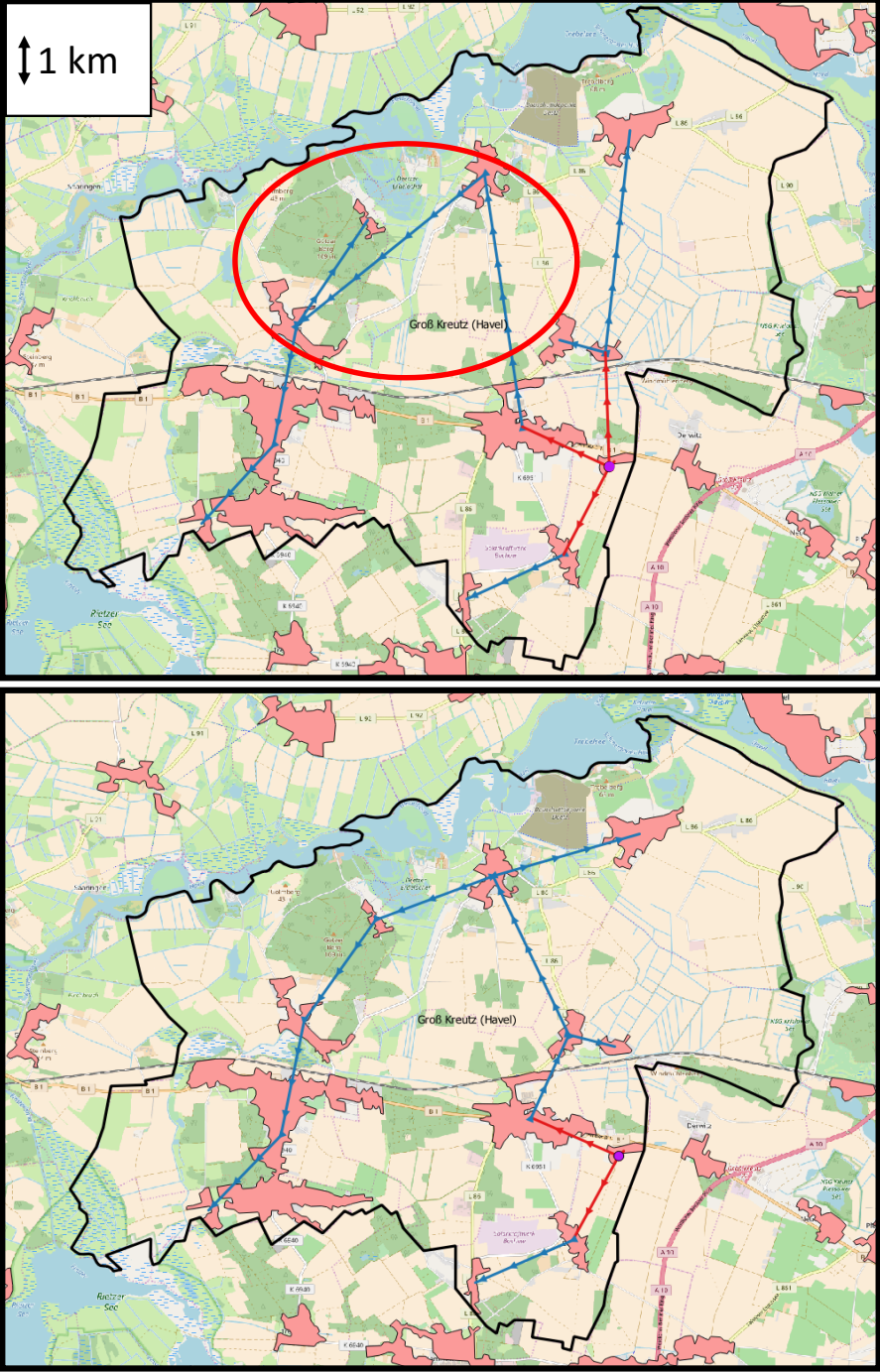


Figure 3: Location of the GTP (purple circle) and DH pipelines to the settlement areas for the target criteria investment per kW (upper part) and costs for the DH pipelines outside the settlements (lower part).

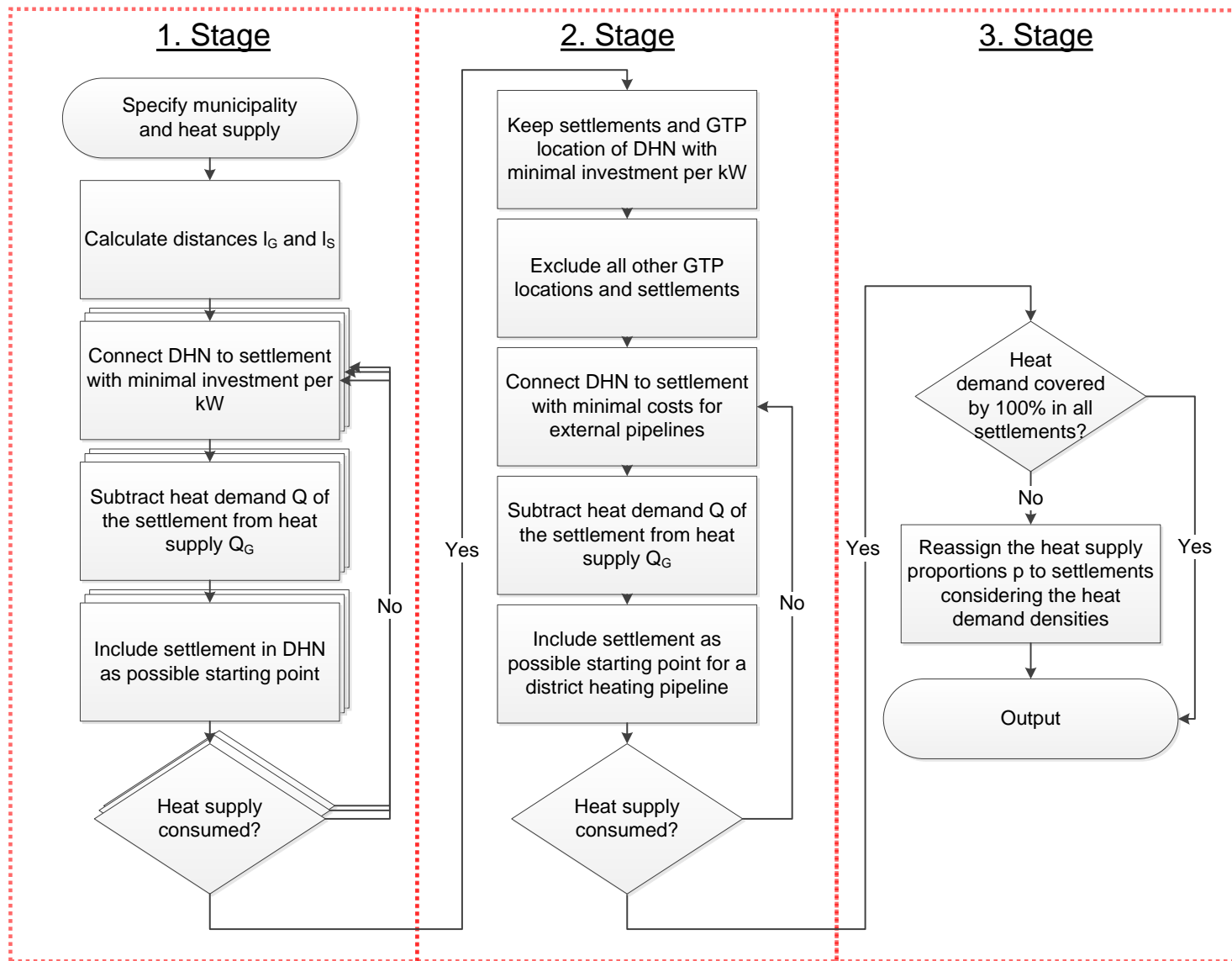


Figure 4: Heuristic for determining the cost-optimal DH system for an arbitrary municipality considering the heat demand, heat densities etc. of the settlements.

4. Results and discussion

In the previous study of Weinand et al. (2018b), the 11,100 German municipalities were clustered into ten groups with regard to their suitability for decentralised energy systems. Two of the 34 socio-energetic indicators in the cluster analysis were used to measure the potential for geothermal energy: the attainable geothermal temperature and the required drilling depth. The municipalities in Germany are suitable for low-temperature GTPs with achievable temperatures up to 190°C. As case studies for the analysis in this paper, four municipalities are selected from the clusters, which have a high potential for geothermal energy (cf. Table 2). Municipalities are selected which differ particularly in the number of settlements, heat demand and the population density. Three of the municipalities are located in the North German Basin (NGB) and Bensheim lies in the Upper Rhine Graben (URG). The parameters of the municipalities important for the following analyses are listed in Table 2.

Table 2: Characteristics of the municipalities examined in this study.

Municipality	Billerbeck	Groß Kreutz	Bensheim	Dümmer
Cluster (in Weinand et al. 2018b)	3	8	3	8
Basin (Agemar et al. 2014)	NGB	NGB	URG	NGB
Area [km ²]	91	99	58	32
Population	11,593	8,133	40,051	1,430
Population density in municipality [1/km ²]	127	82	693	46
Number of Corine settlement areas	3	12	7	5
Average Population density in settlements [1/km ²]	3,000	1,000	3,300	1,300
Yearly heat demand [GWh]	135	55	320	9
Average share of DH in settlements [%]	2	4	2	8

First, the results and the solving time of the optimisation and the heuristic are compared in Section 4.1. The results for the four municipalities from Table 2 are then presented in Section 4.2. Subsequently, the heuristic is examined in a sensitivity analysis in Section 4.3 and discussed in Section 4.4. The results are determined for different heat supplies by DH. Namely, 10% steps were chosen, i.e. the results are shown in the following for heat supplies from the GTP of 10%, 20%, 30%, etc. up to 100% of the heat demand of the municipalities. For example, in the 10% case, the DH system provides 10% of the heat demand in the municipality. The proportion of existing DH systems in the municipalities is subtracted from the heat demand in the settlements.

4.1. Comparison of optimisation and heuristic approaches

The optimisation was carried out in GAMS by using the solver CPLEX and a computer with the following performance properties: Intel Xeon E-1650 v2, 12 threads and 128 GB RAM. The heuristic, however, was executed in Matlab on a computer with Intel Core i5-6200U, 4 threads and 8 GB RAM. The results of the optimisation model and the heuristic are compared for the municipalities of Billerbeck, Dümmer and Bensheim, which contain three, five and seven settlements. The optimisation for Groß Kreutz with more than seven settlements was not

carried out because time constraints already arose during the optimisation for Bensheim with seven settlements. Thus the optimisation for Bensheim had to be terminated after 7 days in the case of 100% heat supply with a MIP gap of 4.8%. Building the equations in Matlab for a municipality with 8 settlements alone would take two hours and the optimisation problem would contain over 100,000 binary variables. In the municipalities of Billerbeck, Dümmer and Bensheim, the equations take between 35 seconds and 12 minutes to build. The time required to build the equations is not included in the following analysis.

Figure 5 shows the percentage by which the calculated total costs are lower in the optimisation compared to the heuristic. In the case of 100% heat supply in Bensheim, the result of the lower bound was adopted due to the above-mentioned termination of the optimisation. The deviation could be much smaller in this case. Therefore, the following analysis will focus on how the deviations in Billerbeck are caused in the 30% to 70% cases and the deviation in Dümmer is caused in the 50% case.

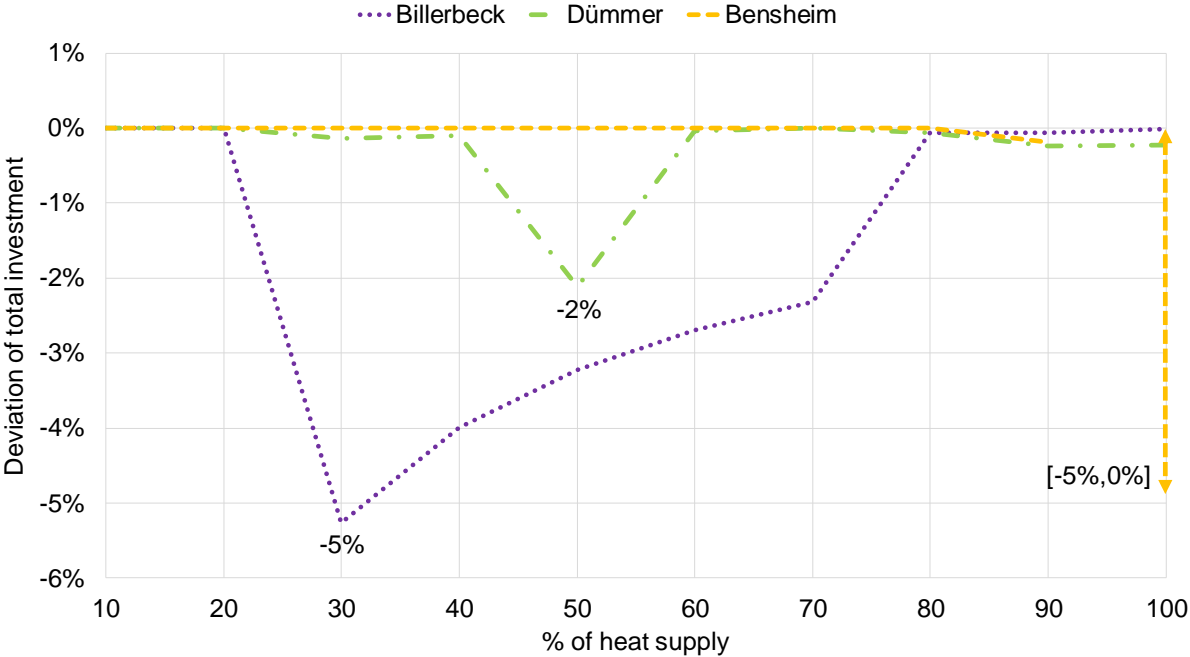


Figure 5: Deviation of the total investment between optimisation and heuristic for the municipalities Billerbeck, Dümmer and Bensheim.

In Billerbeck up to the 20% case, heat is supplied to settlement 2 in the heuristic as well as in the optimisation, since this settlement has the highest building density (for settlement 2 see left part of Figure 6). In the 30% case, however, there would still be heat remaining, so that another settlement has to be supplied with heat. The error is caused by the fact that in the heuristic, after selecting a settlement, the maximum possible amount of heat is supplied to this settlement. Therefore, in the cases 30% to 70%, only settlement 3 with a lower building density than settlement 2 is supplied in the heuristic (cf. left part of Figure 6). By contrast, in the optimisation in these cases, settlement 2 is always supplied entirely with heat and settlement 3

proportionately (cf. right part of Figure 6). Although this means that the costs for the pipelines outside the settlements are higher, the overall costs are lower. After the 30% case, the deviation between optimisation and heuristic decreases further, as the proportion of the heat quantity delivered to settlement 2 becomes smaller and smaller in relation to the total heat.

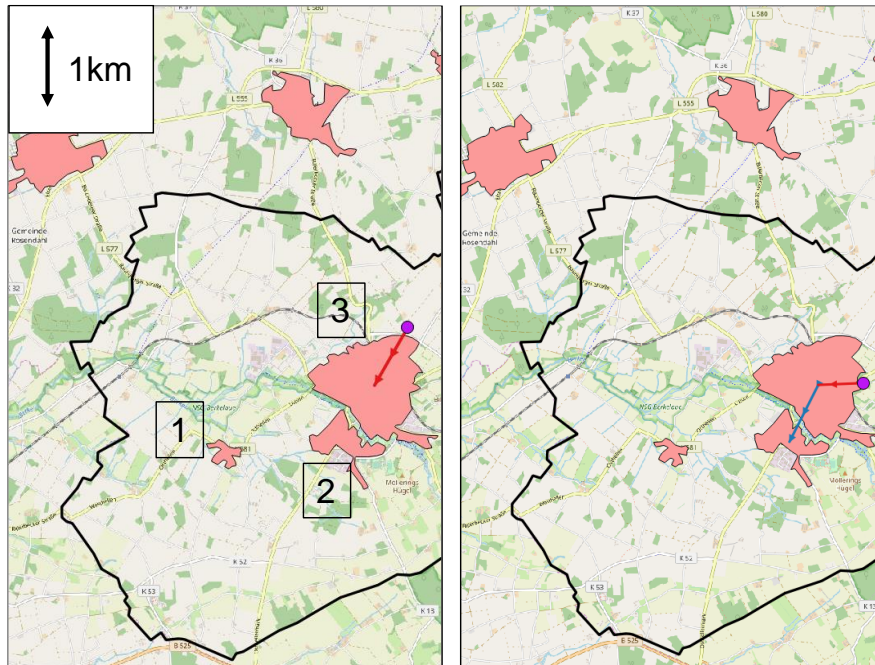


Figure 6: DHN in the 30% case in Billerbeck with the heuristic (left part) and with the optimisation (right part). The settlements are numbered from 1 to 3.

The difference in the municipality of Dümmer in the 50% case is for the same reason as in Billerbeck. The right part of Figure 7 shows the DHN resulting from the optimisation. Here settlement 4 represents an intermediate station and only 15% of the heat demand is covered. This would not be possible in the heuristic again, since settlement 4 would have been supplied with the complete remaining heat supply. Therefore, the more favourable solution in the heuristic is to supply settlement 3 and 5 (cf. left part of Figure 7).

The two discussed examples show that with regard to the amount of heat that is delivered to the settlements, there is still potential for improvement in the heuristic. However, the largest deviation from the optimisation is only 5% and in most cases less than 0.1% of the total investment. If the 100% case in Bensheim is neglected in the calculation due to the termination of the optimisation, a mean absolute percentage error (MAPE) of 0.7% results. As these errors are deemed acceptable for this application the heuristic can be used for estimating DH costs and for planning the DHN including location planning of the plant.

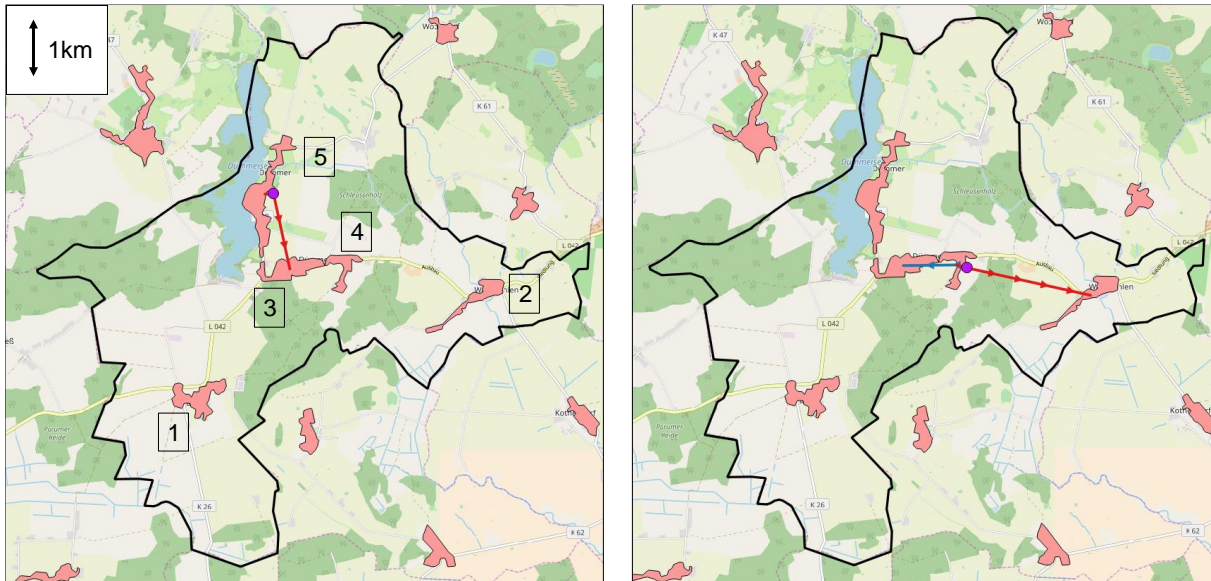


Figure 7: DHN in the 50% case in Dümmer with the heuristic (left part) and with the optimisation (right part). The settlements are numbered from 1 to 5.

Nevertheless, the use of the heuristic would not be reasonable, unless the application contains a significant reduction of the solving time. As Figure 8 shows, the solving time of the heuristic is between 2 and 35 seconds, depending on the case. Leaving aside the 100% case in Billerbeck, the optimisations take between 5 and 100,000 times longer compared to the heuristic. The more settlements that can be connected in a municipality, the longer the optimisation takes (cf. 80% case and 90% case in Bensheim). Whilst the time increases linearly in the heuristic, an exponential increase can be observed in the optimisation. Billerbeck has the fewest settlement areas and yet in some cases the calculations / optimisations take longer than in the other municipalities. This is due to the possible locations of the GTP, of which there are about 200 more in Billerbeck compared to the other two municipalities.

Interpreting the fluctuations of the solution time when optimising the different cases is difficult as no information is known about what causes problems for CPLEX in the specific cases. However, it is certain that the solution space will become smaller or larger, depending on the specified amount of heat. With a duration of up to 7 days, the optimisation would be quite time-consuming. For municipalities with more than seven settlements, optimisation should be avoided at all due to the computing constraints as stated at the beginning of this section.

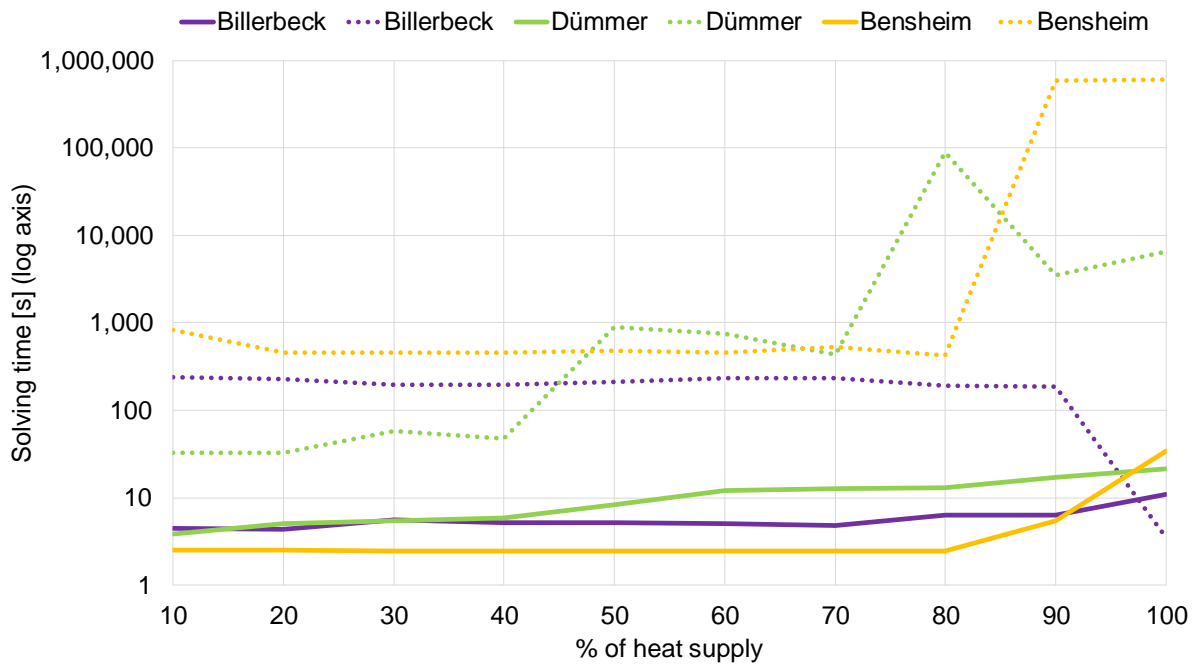


Figure 8: Solving time of the optimisation (dashed lines) and the heuristic (continuous lines) for the municipalities Billerbeck, Dümmer and Bensheim.

In order to show that the heuristic also runs in an acceptable time for larger municipalities, the heuristic was executed for the municipality Gardelegen. This municipality has the eleventh largest number of settlements of all municipalities in Germany with 42 settlements. In total, the calculation of all 10 cases from 10% to 100% took 4 hours. The heuristic was not executed for larger municipalities than Gardelegen, since in this case the limitation to only one heating plant would not be appropriate due to district heating pipelines with a length of more than 100 km.

4.2. Resulting costs for district heating networks

Since the employment of the heuristic was evaluated as appropriate in the previous section, it is applied to the four municipalities from Table 2. Thereby the assumptions from Section 3.1 are used. The comparison of the results reveals the following main interdependencies:

- The higher the household density, the lower the investment.
- The more settlements there are in a municipality and the further apart they are, the higher the costs.
- The smaller the largest settlement, the faster the costs increase with the proportion of heat supplied.

As these findings mainly confirm expectations, no detailed explanation is given in this section, but instead only a few aspects are discussed. The dependency of costs on household density is clarified in Figure 9. The figure shows the investment in relation to the connected heat capacity. The specific connection costs are between 500 €/kW and 1,900 €/kW when using the assumptions from Section 3.1. Bensheim and Billerbeck with the highest household

densities lead to the lowest costs per kW. The specific costs in Bensheim exceed those in Billerbeck at the 100% case in which all settlements are supplied for the first time and thus a long pipeline is built. In Dümmer and Groß Kreutz, the long distances between the settlements play an important role in addition to the low household density, which leads to the high specific costs. If the costs increase more strongly, as in the 50% case in Dümmer, this indicates that more or different settlements are connected to the heating network than in the previous case.

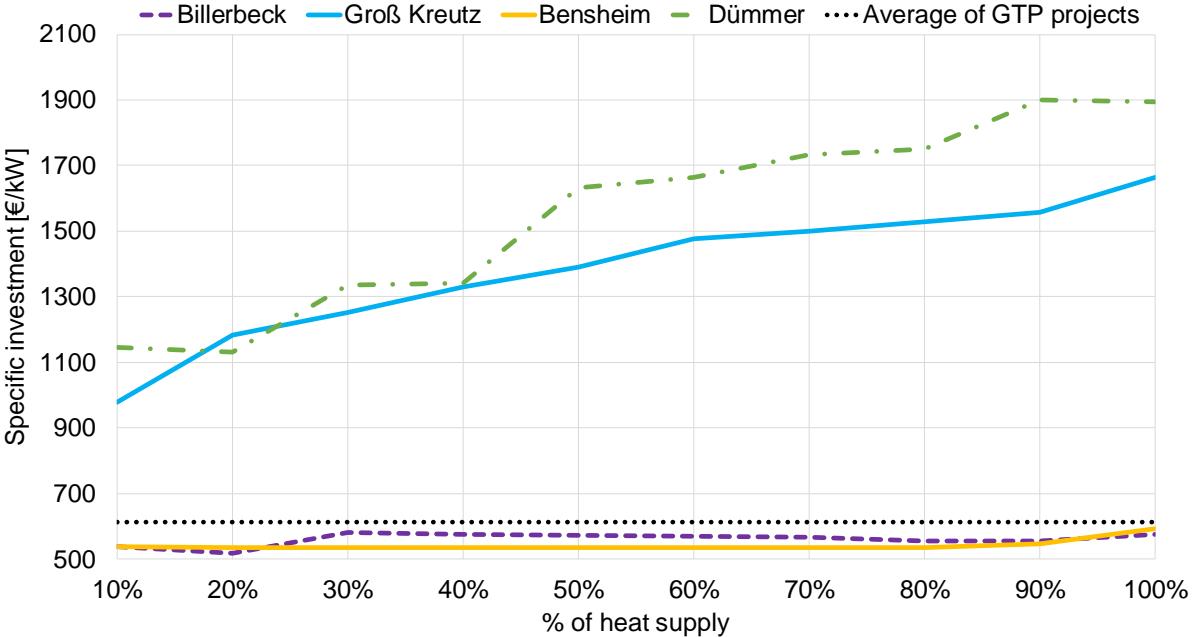


Figure 9: Specific investment per kW for DH pipelines in the four municipalities depending on the proportion of heat supply compared to the mean value from German geothermal DH projects.

The calculated costs in Figure 9 are close to the average costs for the DHN for the geothermal projects Grünwald, Unterföhring, Unterhaching and Neustadt-Glewe of 615 €/kW and can therefore be interpreted as plausible (Enerchange 2009; Enerchange 2018; Erdwärme Grünwald GmbH 2013; Geothermie Unterhaching 2017; GTN 2012). Since the percentage of the heat demand satisfied by the geothermal projects in the municipalities is not known, the 615 €/kW are illustrated as a vertical line. The costs for the municipalities Dümmer, and Groß Kreutz are above this average, as these municipalities have a low building and population density. The costs in the municipalities of Billerbeck and Bensheim with higher building and population density are lower, as the maximum length of the DHN outside the settlements in these municipalities is 3 km and 15 km respectively and therefore below the average network length of 38 km in the above mentioned geothermal projects.

The CO₂ abatement cost curves are similar to those in Figure 9 and lie between 0.7 €/t_{CO2} and 2.4 €/t_{CO2} in the 100% case in Billerbeck and Dümmer respectively. The similar curves result from the fact that the energy mix in the examined municipalities is almost similar, and therefore the amount of CO₂ abatement per kW of district heating is nearly the same.

4.3. Sensitivity analysis

A sensitivity analysis is conducted on the basis of the municipality of Groß Kreutz, which was already used as an example in Section 3. Groß Kreutz is shown again in Figure 10 in reduced form (left side), together with important information in the table on the right side. The black squares represent the centroids of the settlements and above the squares the numbering of the settlements is shown. The red circles indicate the size of the heat demand in the settlements.

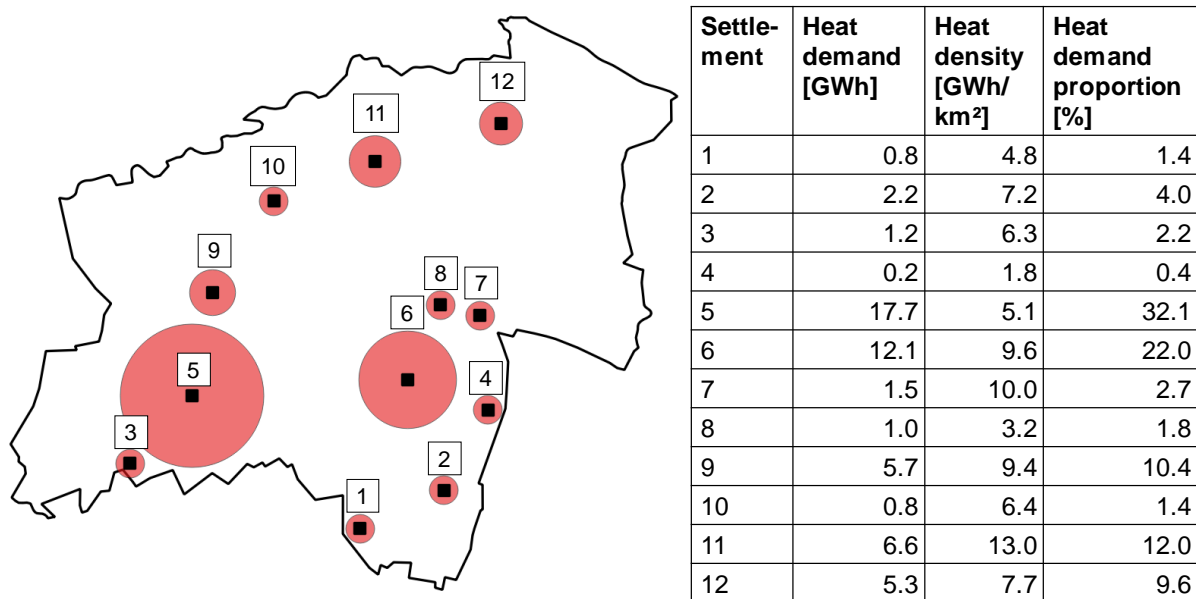


Figure 10: Settlement centroids in the municipality of Groß Kreutz as well as characteristics of the settlements.

The example presented in Section 3 with 497 possible locations for the DH plant as well as the parameters and locations of the settlements shown in Figure 10 represent the reference case for this section. The costs for the reference scenario are determined using the heuristic developed in this study. Table 3 shows, which conditions have been changed as part of the sensitivity analyses in this section. In Section 4.3.1, scenario 1 shows the influence of a modification of the heat density on the solution. The variation regarding the number of possible locations for the DH plant in scenarios 2 to 7 is the subject of Section 4.3.2. Subsequently, Section 4.3.3 explores the impact of the stages of the heuristic using scenarios 8 and 9. Finally, the heuristic developed for this study is compared with the Nearest-Neighbour-Heuristic in this section.

Table 3: Scenarios examined as part of the sensitivity analysis. Changed conditions are shown in italics.

Scenario	Heat density	Number of possible locations for DH plant	Heuristic
Reference	cf. Figure 10	497	Stages 1, 2 and 3
1	<i>Reduced to 0.5 GWh/km² for settlement 5, for the other settlements cf. Figure 10</i>	497	Stages 1, 2 and 3
2	cf. Figure 10	1	Stages 1, 2 and 3
3	cf. Figure 10	9	Stages 1, 2 and 3
4	cf. Figure 10	46	Stages 1, 2 and 3
5	cf. Figure 10	171	Stages 1, 2 and 3
6	cf. Figure 10	1299	Stages 1, 2 and 3
7	cf. Figure 10	2749	Stages 1, 2 and 3
8	cf. Figure 10	497	<i>Stage 1</i>
9	cf. Figure 10	497	<i>Stages 1 and 2</i>
10	cf. Figure 10	497	<i>Nearest-Neighbour-Heuristic</i>

Figure 11 shows the deviation of the total costs in scenarios 1 to 10 compared to the reference case for 10% heat supply steps. For reasons of clarity, continuous deviations of less than 1.5% have been removed from Figure 11. Therefore, the curves for scenarios 6 and 9 are not shown at all. In the following sections the figure is explained in more detail.

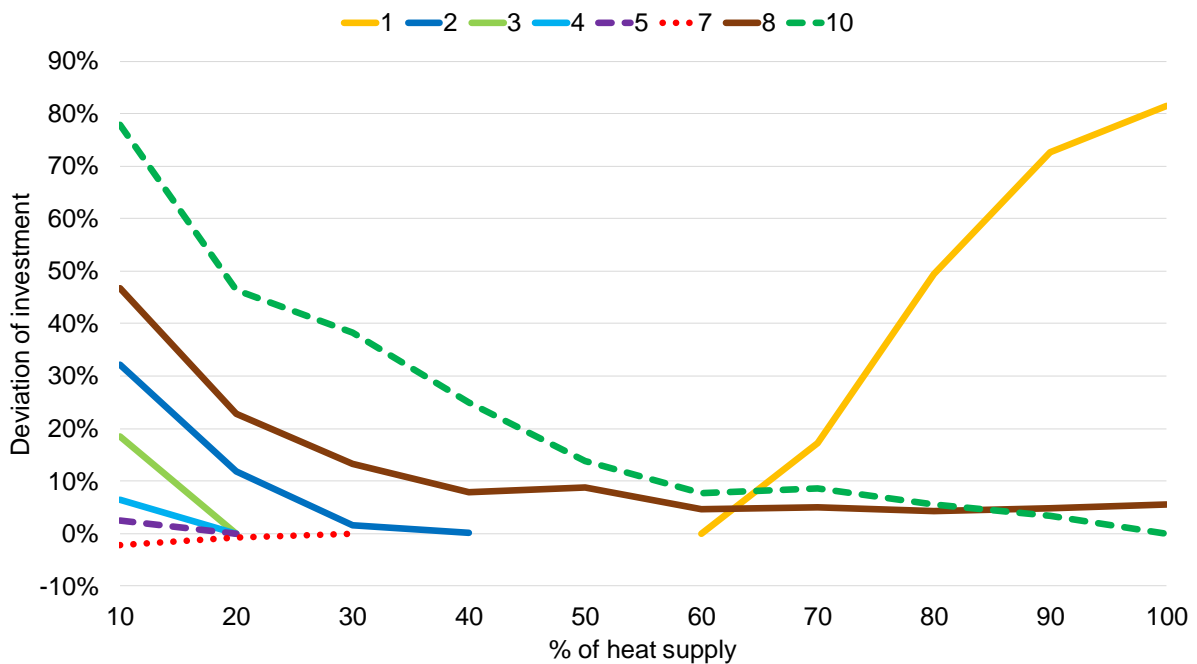


Figure 11: Deviations in the total costs for scenarios 1 to 10 in relation to the reference scenario.

4.3.1. Heat demand and heat density

On the left side of Figure 12 the reference case with 70% heat coverage is shown. The five settlements 5, 6, 9, 11 and 12 with the highest heat demand are connected to the DH plant in this case. To examine the sensitivity in scenario 1, the heat density is now reduced from 5.1 to 0.5 GWh/km² in the settlement 5 with the highest heat demand. Settlement 5 must be partially supplied in order to cover 70% of the heat demand in the municipality, as it accounts for more than 30% of the total heat demand (cf. table in Figure 10). All other settlements, except settlement 4, are now connected to the DHN to ensure that as few households as possible are connected in settlement 5 (cf. right part of Figure 12). Settlement 4 also has a very low heat density and heat demand, therefore the pipeline to this settlement is not worthwhile.

In the 60% case, settlement 5 is not connected to the DHN at all. In comparison to the reference scenario, the costs increase strongly in scenario 1 if settlement 5 is included in the solution. Thus the total costs increase in the 70% case only by 17%, while in the 100% case the costs increase by over 80%, since settlement 5 is completely supplied with heat (cf. Figure 11).

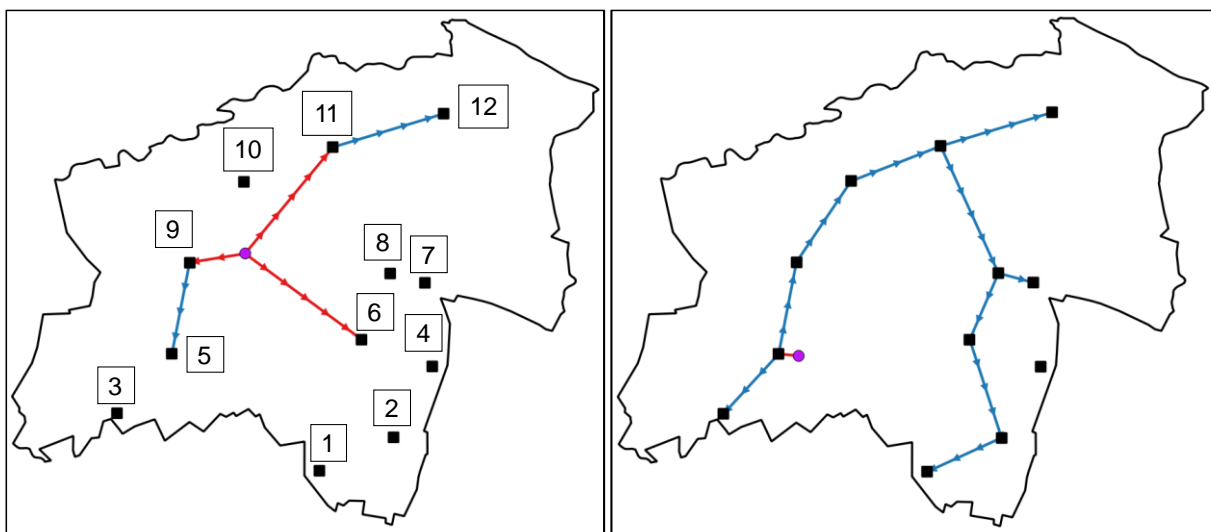


Figure 12: Location of the DH plant and DHN with a heat supply of 70% of the heat demand in Groß Kreutz in the reference case (left part) and for scenario 1 (right part).

4.3.2. Number of locations

As already described in Section 3, when determining the possible locations of the DH plant, the number of locations between the minimum and maximum coordinates of the municipality is specified. 1, 5, 10, 20, 55 and 80 locations are defined for the scenarios 2 to 7 respectively. The potential locations for the scenarios are illustrated in Figure 13, with the resulting number of locations shown in parentheses under the scenario names. In cases with a lower percentage of heat supply, the number of locations has the greatest impact on the total costs, as the costs for the pipelines outside the settlements account for a larger share. Thus the costs in the 10%

case in scenario 2 are 32% higher than in the reference case with 497 locations (cf. Figure 11). With a rising number of potential locations from scenario 2 to scenario 5, however, the costs increasingly match with the costs in the reference scenario. In scenario 6 there are only very small deviations, so the curve is not shown in Figure 11. A further increase in the number of locations in scenario 7 also reduces the costs only marginally.

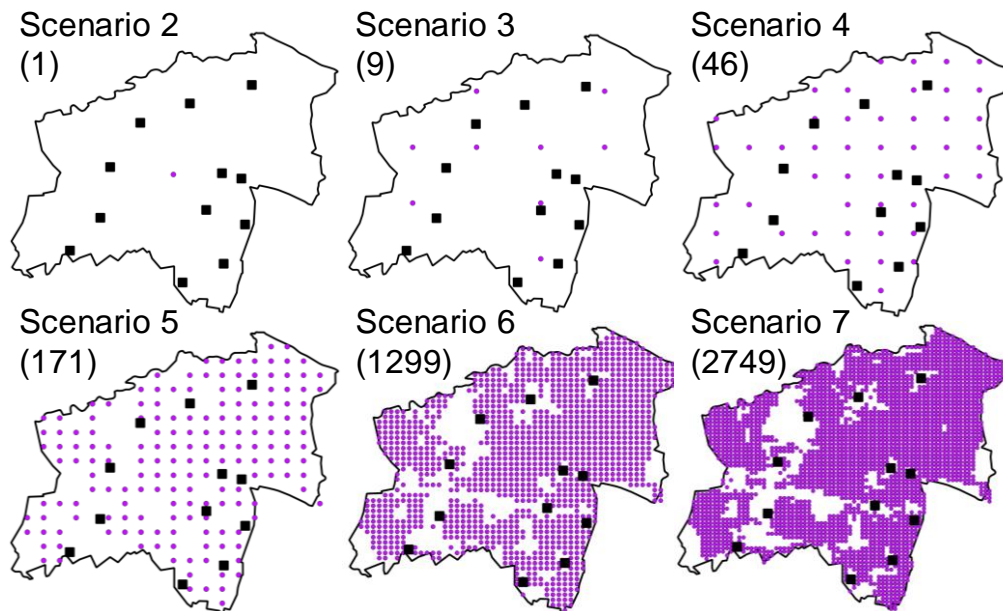


Figure 13: Possible locations for the DH plant in scenarios 2 to 7. The resulting number of locations is shown in parentheses under the scenario names.

As shown, the costs in the scenarios change due to the varying distance of the DH plant to the settlements. Therefore the costs are calculated again for the reference scenario and scenarios 2 to 7, however, this time with costs for the pipelines outside the settlements of 500 €/m instead of 200 €/m. As a result of this adjustment, deviations also occur in the cases with higher heat supply proportions and the other deviations increase strongly. For example, the deviations in scenario 2 increase from 32% to 68% in the 10% case. The cost of pipelines outside settlements now accounts for up to 35% of total costs in scenarios 2 to 7 instead of up to 20% in the case with pipeline costs of 200 €/m. Even with 500 €/m the costs decrease only slightly compared to the reference scenario in scenarios 6 and 7. With rising number of locations, the time for solving the heuristic increases linearly. Thus the selection of the 497 locations for the municipality Groß Kreutz can be evaluated as reasonable. Therefore, a number of 5 locations per km² can be recommended for the study of other municipalities considering the size of Groß Kreutz.

4.3.3. Number of stages

Section 3 and Figure 3 have already indicated that an appropriate DHN is not achieved by performing only stage 1 of the heuristic. Since the settlements are iteratively connected to the

DHN, the optimal connections rarely arise. This is reflected in the costs of scenario 8, which are at least 5% and on average 12% above the costs of the reference scenario for each case (cf. Figure 11). Considering the reference scenario and scenario 8 with pipeline costs of 500 €/m instead of 200 €/m, the costs in scenario 8 increase on average by 30%. The omission of step 3 in scenario 9 results in a slight cost increase of no more than 1.3%, so that the curve is not illustrated in Figure 11. However, the third stage leads to slight improvements and should be executed as it has negligible influence on the solution time.

In scenario 10, a standard algorithm is used to demonstrate the performance of the heuristic developed in this study. Thereby, the heuristic of this study is applied with a modified target criterion: the Nearest-Neighbour-Heuristic connects the nearest settlement to the DHN in each iteration. The DHN in the reference case on the left side in Figure 12 could therefore never result with this heuristic. Instead of settlement 12, which is the furthest away from all other settlements, the Nearest-Neighbour-Heuristic connects settlements 3 and 10 in the 70% case (cf. Figure 14). In the next step, settlement 8 would be connected, which is 1.76 km away from settlement 6. The Nearest-Neighbour-Heuristic would be considered if only stage 1 of the heuristic developed in this study would be executed with the target criterion of stage 2.

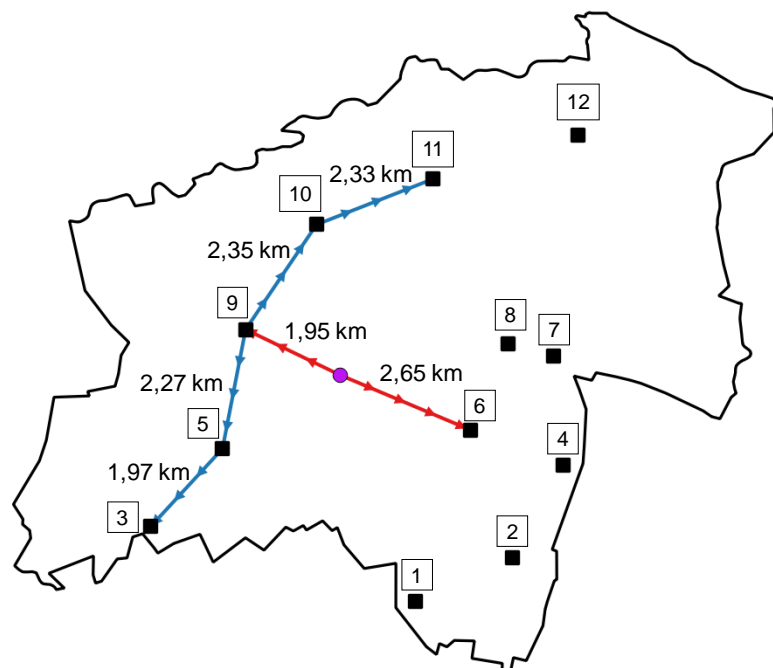


Figure 14: Location of the DH plant and DHN in the 70% case resulting from the Nearest-Neighbour-Heuristic.

As shown in Figure 11, the Nearest-Neighbour-Heuristic results in significantly higher costs than the reference scenario. The deviations reach values of up to 78%. Obviously, the more heat demand is covered in the municipality, the lower the deviations will be until the costs match in the 100% case. The calculation of the nine cases up to the 90% case requires between 50% and 250% more time compared to the reference scenario, as more settlements

are connected. The results of this section indicate again that the application of the heuristic in three steps is reasonable.

4.4. Critical appraisal

The sensitivity analyses in Section 4.3 revealed that the heuristic developed in this study yields better results than simpler heuristics, especially in the case of low heat coverage in the municipalities. The current distribution in Germany indicates that these rather low heat coverages in municipalities through DH are of importance as in municipalities that already have DH systems, the average proportion of DH systems in all heating technologies is just 3.5% (Statistisches Bundesamt 2014). This share is lower than the share of district heating in the total German heat supply of 13.8% (cf. Section 1), as all municipalities are equally weighted in the calculation. For high heat coverages, e.g. the 100% case, simpler heuristics such as the Nearest-Neighbour-Heuristic are also suitable. However, since this takes more time than our heuristic, it is not recommended to use it.

The heuristic can be used in this form or slightly modified for DH plants different to GTPs. This would only require a change in the possible locations of the DH plant. For other plant types, the location could even be within a settlement.

In this study, the developed heuristic was applied to individual municipalities. However, the applicability of the heuristic is not limited to this administrative level. The heuristic can also be used for other regions with little effort. Figure 15, for example, shows the simultaneous application to four municipalities. This is an important aspect, since energy system analyses should not be limited to individual municipalities, but should determine the optimal aggregation level for the energy system. In small municipalities, the construction of a GTP would probably not be worthwhile as the fixed costs of these plants are very high. However, if several municipalities are involved in the analysis, the construction of such a plant could become economically viable.

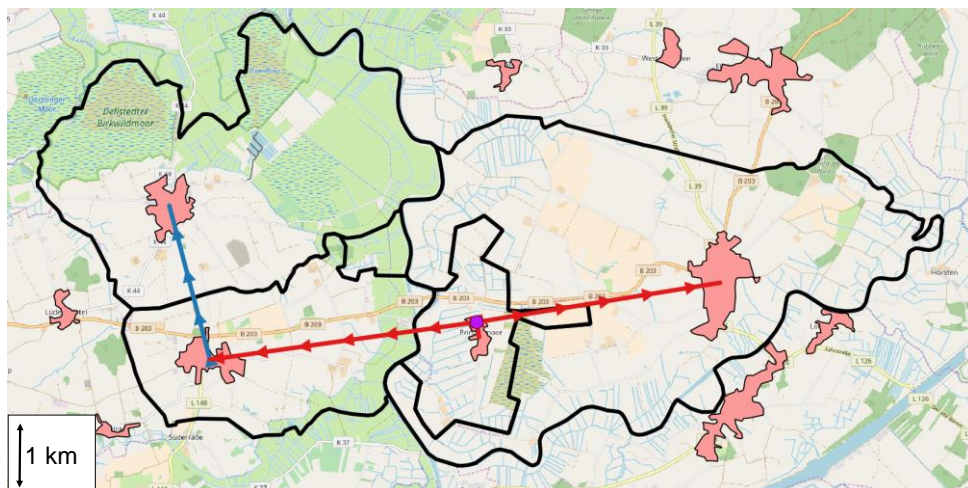


Figure 15: Result of the heuristic if applied to several small municipalities in northern Germany.

In addition, the heuristic can be easily applied to other countries. In this case, the heat demand as well as the population and building density for each settlement have to be determined as in Weinand et al. (2018a). The Corine land use areas were determined for 38 other European countries besides Germany and can be used as a basis (EEA 2018).

For the study presented here, improvements can be made in a couple of areas. First of all, the optimisations in this study do not always yield the realistic optimum. This is due to the fact that, in reality, the pipelines cannot always run straight ahead and no local topological conditions are taken into account. It is further neglected that a pipeline could be divided into two or more pipelines in order to connect several settlements with a pipeline starting from one settlement. In order to overcome this problem, many points could be introduced as possible branches in further work, such as the points of the GTPs in Figure 3, at which pipelines can divide. However, the investment would probably not be significantly reduced. In addition, since the centroids of the settlements are used as connection points and not the border of a settlement, the costs for pipelines outside the settlements are slightly overestimated.

Furthermore, the feasibility of GTPs depends strongly on the local geological conditions. This means that the GTP location determined by the heuristic may not be technically feasible at all. In this case, the location could be excluded and the heuristic could be executed again. On the other hand, a location could also be specified beforehand and the heuristic could be used to only determine the connections of the pipelines. In addition, some locations for the GTP could be manually excluded in advance, as it is visible that these are not optimal due to far distance to the settlements (cf. Figure 3). However, due to the short time required by the heuristic, this is not necessary.

The use of a constant heat loss via an efficiency and thus the neglect of heat losses per kilometre also means that the optimal location of the GTP and the optimal DHN are not necessarily determined. If the specific heat losses were taken into account, the GTP in Figure 3 would probably be closer to the largest settlement on the left-hand side of the figure. This is due to the fact that a large amount of heat could then be supplied without a large heat loss occurring before. However, a different location of the GTP than in the optimal case would not increase the costs significantly. Nevertheless, the heuristic should be improved in further work with regard to heat losses. Related to this, pressure losses should also be taken into account in future work. These make further district heat pumps necessary at certain points in the DHN. In the case of an optimisation model, non-linear equations would have to be integrated into the model, to take the properties mentioned in this paragraph into account (Bordin et al. 2016).

It has been described above that the DH share in German municipalities is on average 3.5%, but there are also municipalities with a high DH share of over 90%. In future studies, it is therefore necessary to extend the heuristic in such a way that existing networks can be

recognised as well as used to integrate the heat and thus reduce the investment for pipelines. As already explained, the share of existing DH is only deducted from the heat demand in this study. One possibility would be to apply the methodology of Blanco et al. (2017) which has been mentioned in Section 2.3. Uncertainty about the location of heat consumers could take into account the fact that it is not known where district heating connections already exist and where the greatest heat demand within a settlement exists.

Additionally, the results of the heuristic and optimisation could only be compared for municipalities with less than eight settlements in Section 4.1. The analysis gives no reason to believe so, however, the results of the heuristic and the optimisation may differ more strongly for municipalities with more than seven settlements. Even if this would be the case, in most instances the heuristic could be used sensibly, since about 80% of the German municipalities contain less than eight settlements.

Finally, this study assumes that the GTP can be operated during the whole year. This would rarely be the case in reality due to e.g. maintenance intervals. However, this fact is irrelevant for the design of the DHNs. The outage times could be avoided by different technical measures, like a modular construction of the plant, in which the plant parts exist multiply and broken parts can be replaced temporarily or by using heat storages.

5. Conclusions

Against the background of a trend towards decentralised and community-owned energy systems, this paper develops a method to set up a minimum-cost geothermal-based municipal district heating (DH) system. To this end, two approaches based on combinatorial optimisation were presented, in order to support local planners in the design of geothermal DH systems. The first approach involves a combinatorial optimisation of the DH network layout, including geothermal plant location and network topology, which is applicable to municipalities with less than eight discrete settlement areas. The second approach is a three-stage heuristic, which serves the same purpose but can be applied to a much higher number of municipalities with many more settlement areas.

One of the innovations of the developed optimisation model and the developed three-stage heuristic compared to previous work is the fact that not only the DH network, but also the location of the DH plant, is optimised. Furthermore, the nodes / settlements to be connected are not fixed in advance and do not have to be supplied completely with heat. The two approaches presented in this work can easily be applied to every municipality in Germany and the methodology could be easily extended to 38 other European countries.

A comparison of optimisation and heuristic for three exemplary municipalities demonstrates the efficiency of the developed heuristic. For municipalities with three, five and seven

settlements respectively, the optimisation takes between 500% and 10,000,000% more time than the heuristic. The resulting deviations in the calculated total investment for the DH from the results of the optimisation are in all cases below 5% and in 80% of cases below 0.3%. The efficiency of the heuristic is demonstrated by the comparison with simpler heuristics like the Nearest-Neighbour-Heuristic. The latter is not only less efficient, it substantially overestimates the total costs by up to 80% in all cases with less than 100% DH heat coverage. In addition, the calculated investments in the investigated municipalities ranged from 500 €/kW to 1,900 €/kW, values which could be validated with investments for existing geothermal DH networks in Germany.

The developed heuristic consistently yields results within acceptable margins of error of its equivalent combinatorial optimisation problem, is efficient and scales well to other regions or contexts. The developed methodology would benefit from some further improvements, for example some of the technical aspects such as heat and pressure losses within the DH network could be modelled more precisely in the heuristic. This would be particularly important in order to plan the DH network within the municipality, which is considered beyond the scope of this contribution. Furthermore, additional geological and topological conditions in the municipalities should be taken into account in order to better identify the optimal location of the geothermal plant and the type of network. Finally, the heuristic should be extended in such a way that the DH pipelines can also branch off in order to reach several endpoints from one starting point. All of these aspects remain areas for future work and will be the subject of a forthcoming contribution, alongside a more holistic energy system analysis (as shown in the appendix/supplementary material).

Notwithstanding these shortcomings, the developed method, comprising combinatorial optimisation and heuristic, provides a sound basis for decision support for municipal-scale geothermal DH systems. The heuristic for cost-optimised placement of the geothermal plant provided as supplementary material can be easily extended and should offer useful insights for local planners and authorities when considering the heat source options at their disposal.

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Appendix

A.1. Nomenclature

Variable / Parameter	Description	Unit
$b_{DH,S}$	Binary variable for deciding which proportion of the head demand in the municipality should be covered by district heating	-
b_{GL}	Binary variable for deciding whether a geothermal plant should be built at a specific location	-
b_{GS}	Binary variable for deciding whether a settlement can be reached by a certain path	-
c_p	Specific costs for pipelines outside the settlements	€/m
$C_{pipe,in}$	Investment for district heating pipelines inside a settlement	€
$C_{pipe,out}$	Investment for district heating pipelines outside a settlement	€
c_s	Investment for one district heating substation	€
C_{sub}	Investment for all district heating substations	€
C_{total}	Investment for the entire district heating network	€
D_{heat}	Heat demand of the municipality	kWh
HDC	Specific heat distribution costs	€/kWh
l_G	Distance between a district heating plant and a settlement	m
l_s	Distance between two settlements	m
M	Represents a big number	-
N_s	Number of district heating substations	-
p	Specifies which proportion of the heat demand in a settlement is covered by district heating	-
\dot{Q}	Heat supply to a settlement	kWh
\dot{Q}_G	Heat generation of a geothermal plant	kWh
x_G	Binary variable for deciding whether a district heating pipeline between a district heating plant and a settlement should be built	-
x_s	Binary variable for deciding whether a district heating pipeline between two settlements should be built	-

A.2. Application in an energy system optimisation

In energy system analyses, it is very important that different technologies are weighed against each other and are dimensioned at this stage and not beforehand. Due to the complex interconnections in such analyses, the choice of appropriate technologies and the dimensioning is difficult. Other heat generation technologies and measures such as the insulation of buildings need to be compared with DH in these assessments. The easily

transferable approach presented in this section shows a way to dimension the geothermal DHN that can be integrated into energy system analyses.

Therefore, the results of the optimisation from Section 3.2 or the heuristic from Section 3.3 could be used. In order to take into account the energy flows between the settlements, the municipality should not be optimised as a whole but divided into districts. This ensures that DH is only supplied to households connected to the DHN. Voronoi clustering by means of the settlement centroids could be implemented to divide the municipality into districts (cf. Figure 16). This division is also necessary to assign other potentials such as electricity generation from photovoltaics or wind plants to the settlements.

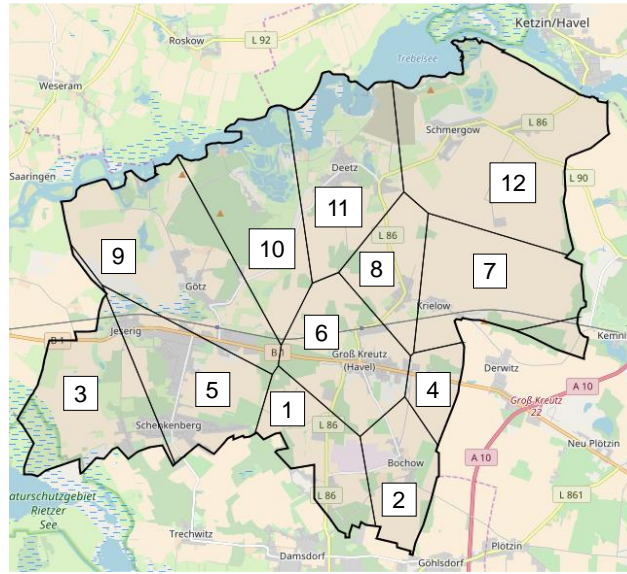


Figure 16: Voronoi Cluster with the help of settlement centroids in the municipality Groß Kreutz.

With the help of the resulting districts, the optimisation model can specify from where to which district the DH can be distributed. The costs for the DH system could then be calculated in several percentage steps. In the following a segmentation into 10 steps is done, i.e. with supply of 10%, 20%, 30% etc. up to 100% of the heat demand. The pipeline connections then depend on the choice of the binary variable $b_{DH,S,i}$ (cf. Eq. 12).

$$\sum_{i=1}^{10} b_{DH,S,i} \leq 1 \quad 12$$

For example, if the DHN from the lower part of Figure 3 should be built, i.e. all settlement areas could be supplied with DH, then $b_{DH,S,10}$ has to be set to 1. By selecting the binary variables, the nominal output \dot{Q}_G of the DH plant can also be limited by a proportion of the heat demand of the municipality D_{heat} (cf. Eq. 13).

$$\dot{Q}_G(t) \leq \sum_{i=1}^9 (b_{DH,S,i} \cdot 10\% \cdot i \cdot D_{heat}(t)) + (b_{DH,S,10} \cdot M) \quad 13$$

The case with 100% is not included in the sum so that more DH can be generated than required. Therefore, the binary variable is multiplied by a large number M . In addition the investment for and CO_2 abatement of the DH system are selected with the binary variable.

In the heuristic, the heat losses are taken into account via a constant efficiency, which therefore has no influence on the choice of the network. In energy system optimisation, heat losses should therefore also be taken into account, depending on the length of the network. Heat losses of 0.5%-3% per km, depending on the capacity of the pipeline, have to be taken into account for the pipelines (Danish Energy Agency 2017). This is also important for the dimensioning of the GTP.

Another issue is the designing of the DHN before the global optimisation. Would the designing of the DHN be integrated in the global optimisation, other connecting pipelines could result than calculated before with the heuristic. In the heuristic, for example, a connection to settlement 5 could be worthwhile in the case of a 50% heat supply. In the global optimisation, on the other hand, settlement 5 could ideally be supplied by other heating technologies than district heating. Then this settlement would have to be excluded in the heuristic and another solution would result in the case of a 50% heat supply. This problem could be mitigated by an iterative approach, where the heuristic is executed again after the global optimisation and the global optimisation is then executed again with the new solution. However, this would require a lot of computing time. On the other hand, these discrete options are usual in global energy system optimisations. Even without the above-mentioned iterations, there would still be added value compared to the studies mentioned in Section 2.1 as the DHN could now be dimensioned in the global optimisation.

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