Potentials for district heating generation in a climate-neutral energy system

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Abstract:

In order to achieve climate-neutrality in the building sector, renovation of the building stock and decarbonisation of heat supply is required. District heating is a possibility to supply buildings with heat from different sources. In the future, renewable sources and excess heat will provide carbon-neutral heat for the heating of buildings, replacing fossil-fuelled CHP plants. These sources are spatially limited. Here, we show that the technical potentials of geothermal energy, excess heat from industry and waste incineration as well as heat from rivers and waste water plants together with heat pumps can supply the annual district heating demand in Germany in 2050. Full load hours were used to reflect on seasonal availability of the sources. Technical parameters with uncertainties are varied and show a medium impact on the results on a possible supply of future district heating systems. Distance analysis is used to allocate the generation potentials to DH areas, based on maximum distances. The results were grouped in a cluster analysis, showing that six clusters are sufficient to describe the typologies of the district heating areas in terms of supply potentials. The results lead to the conclusion, that together with biomass, solar thermal and peak load boilers, the district heating demand can be supplied by carbon-neutral heat sources in the future.

Keywords: heat supply; industrial excess heat; district heating; geographical information system; spatial analysis, scenario analysis

1 Background

In the future, district heating (DH) can be a central pillar for an efficient and climate-neutral heat supply for buildings [1,2]. Reaching the climate targets for Germany necessitates doubling the share of today's DH supply to residential buildings, supplying in 2045 up to 26% of residential floor area [3]. In 2018, fossil fuels had a share of 63.7% in district heating generation in Germany [4]. As part of the transformation of the energy system towards climate neutrality [5,6] the generation of DH must therefore be decarbonised. Possible options are the use of renewable heat sources such as solar and geothermal energy, direct use of waste heat or use of low-temperature heat with the help of heat pumps. These potentials are spatially limited. In this paper, the question is answered how renewable heat and waste heat can cover the future DH demand in Germany and which technology assumptions have a major influence.

The aim of this study is to analyse the available heat sources from renewable sources and excess heat from industry for each DH area in Germany. The methodology and technical assumptions are verified to be suitable for covering country- and EU-wide extent. The results from this analysis can be used to model the dispatch and thus the economic potential of each source, as well identify the need for heat storages and electric or gas boilers to cover the peak load.

2 Data and Methodology

Potential DH areas and possible heat sources for the year 2050 are analysed in a Geographical Information System (GIS), assuming that there are no fossil sources left in the energy system for DH generation in 2050. The spatial proximity as well as seasonal coverage of supply and demand is decisive for this [7–9]. In this study, the focus lies on the spatial proximity of sources and demand, on the basis of annual values. The seasonal variation is integrated by assuming typical full load hours rather than by matching hourly load curves. In general, technical potentials in terms of available energy per year are analysed, hence economic parameters are not considered. To some extent however, the derived technical potentials take into account typical sizes of projects (e.g. river heat pumps) as well as economically maximum distances of heat sources to DH areas based on average energy amounts. Thus, the potentials derived do not reflect the total technical potential.

In the following, the methodology for analysing future DH demand and supply is introduced, together with the assumed values. In Table 1, the heat sources are listed, together with the most important parameters.

It should be noted, that solar thermal potentials and available biomass were not mapped to the DH areas in this study. It is assumed, that these potentials are not limited by the spatial availability. More likely, biomass can be transported to some extent and solar thermal plants will be built according to an economic analysis of how much energy they can provide in summer and to long-term storages. Thus, rather the economic potential than the technical potential of solar thermal and biomass energy is relevant.

Table 1: Important parameters that are assumed and varied for considered heat generation potentials

Heat Generation Potential	**Spatial resolution**	**Temporal resolution**	**Considered temperature level**	**Maximum distance from source**	**Parameters**	**Source**
Geothermal	1 km²	Annual, full load hours considered	>60 °C	15 km	Full load hours, injection temperature	Geothermal Atlas [10]
Industrial excess heat	Coordinates	Annual, monthly profile considered	> 55 °C	20 km	Temperature	ISI Industrial Database [1]
Waste incineration	Coordinates	Annual values	100 °C	10 km	No variation	Peta 5 [11]
Rivers and lakes with heat pump	0.5 km²	Annual, full load hours considered	2 – 8 °C	5 km	Minimal temperature, full load hours	Copernicus [12]
Waste water treatment with heat pump	Coordinates	Annual values	10 - 25 °C	2 km	No variation	Peta 5[11], Hotmaps [13]

2.1 DH Areas

The potential DH areas are modelled by analysing the spatial building stock and thus the heat density [14]. The Hotmaps heat demand density and gross floor area density maps for the base year of 2015 are the main input data for the calculation [13]. The regionalized renovation scenario developed in the model Invert/EE-Lab on NUTS 3 level is fed into the Hotmaps demand projection calculation module, to generate future heat demand and gross floor area densities on a hectare level [2,15,16]. Invert/OPT calculates the market share of different supply technologies. This is used as a basis for the identification of the DH market share in the beginning and end of the study horizon. The 2020 heat demand in each hectare is modified linearly to reach to its value in 2050. Accordingly, the DH connection rate in each hectare is projected from 2020 to 2050. The assumed grid cost ceiling plays an important role in the identification of the extent of the DH areas. The levelized cost of DH distribution grid in each DH area may not exceed the grid cost ceiling. Under constant input parameters, increasing the grid cost ceiling leads to extension of DH areas to areas with lower heat demand densities.

In this study, coherent areas with an annual heat demand of less than 10 GWh are excluded from DH areas. An interest rate of 2% is considered for the annuity calculations. A combination of 35% and 45% connection rates in the start and the end year besides a grid cost ceiling of 27 €/MWh complies with the Invert/OPT scenario for Germany. The possible heat use from possible sources is considered under the assumption of varying diffusion of low-temperature grids and thus lower return flow temperature level (4GDH - "4th generation", see [17]) until 2050.

2.2 Geothermal

Geothermal energy is available at different temperature levels at different depths. The technical geothermal supply potential is defined as the potential that could be extracted technically from the underground. Principally, a geothermal plant includes one injection and one extraction borehole. The extraction borehole pumps water to the surface that stores the heat energy from the underground. The geothermal plant extracts the energy, depending on the temperature, e.g. with a steam process, organic rankine cycle or with a heat pump. After that, the cooled fluid is injected back to the underground with a second borehole, typically about 1 km away. There are two different possibilities to extract the heat with deep geothermal plants: hydrothermal and petrothermal. Hydrothermal plants use hot water basins within depths of typical 2000 - 4000m and extract the thermal water. Most of existing plants are hydrothermal, as they have higher flow rates and thus economic advantages. However, it is necessary to map the underground to locate these hydrothermal resources by test drillings (exploration risks). Petrothermal projects do not rely on hot water reservoirs underground, but extract the heat from the solid rock by injecting water that is heated up by the hot rock. In general, this potential is available almost everywhere, but the flow rates and maximum power is lower and so far only few economic petrothermal projects have been realised [18].

In this study, the petrothermal potential is analysed. As in some of the regions also hydrothermal potentials could exist, the local geothermal potential could be actually higher. Even though hydrothermal reservoir maps are published, they cover only regions. Thus, an analysis of hydrothermal potentials is not suitable for European scale, just due to lack of data.

Estimating the petrothermal potential depends mostly on the temperature variation in the underground in different depths. In the European atlas of geothermal resources [10], maps are available for temperature gradients in 1000m and 2000m depth. The temperature data of the underground is extracted as a raster file with the resolution of 1000m x 1000m. Each cell represents the temperature of the underground at the depth of 2000m. As petrothermal projects are typically deeper due to higher temperatures, the depth of 2000m up to 3000m is considered here. The average temperature gradient is 30K/1000m, therefore 15K were added to the temperatures in the raster data to have an average value for this analysed underground layer. Excluded were regions with national parks, mountains and elevation higher than 500m, as well as water areas.

To calculate the available petrothermal power P, typical petrothermal flow rates Q and the temperature of the underground are used, similar to [18]:

$$P = Q \times \rho_W \times c_W \times (T_1 - T_2), \qquad (1)$$

with T_1 as the temperature in the underground in the depth of 3000m, and T_2 as the temperature of the injected water. As the volumetric flow rate is assumed, the density of the water ρ_W is needed. Furthermore, the heat capacity c_W of the water is assumed:

$Q = 25\ \frac{l}{s}$ [18] up to $50 \frac{m^3}{h}$ [19] for petrothermal projects, the average value of $0.0194\ \frac{m^3}{s}$ is used,

$\rho_W = 1000\ \frac{kg}{m^3}$,

$c_W = 4000\ \frac{J}{kg\ K}$,

$T_2 = 40, 50, 60\ °C$.

The injection temperature highly depends on the system design, future temperature levels in the DH systems and technological progress as injection temperatures below 60 °C can lead to scaling in the heat exchanger or pipes [18]. Hence, the injection temperature is varied from 40 to 60°C in steps of 10K.

The minimum temperature of the underground is assumed to be at least 15K higher than the injection temperature T_2, in order to ensure a sufficient temperature spread of injection and extraction water. Therefore, depending on the assumed injection temperature, areas with lower temperatures than the threshold value were excluded. Furthermore, a risk factor of 50% similar to [18] is included, as not all boreholes will show the sufficient flow rate.

The potential in MW is calculated for each raster pixel of the map, with a maximum distance of 15 km to the DH area. This potential should reflect the maximum heat that can be extracted by one project. However, the minimum distance between projects and therefore the boreholes pairs (injection and extraction) needs to be considered. The area needed per borehole pair is 6.93km² [18], so the potential per raster pixel is adapted.

As a last step, the annual energy from the underground is estimated by assuming future full load hours. As they again depend on the system design of each project and future temperature levels, full load hours of 3000h and 4000h are considered and compared.

2.3 Excess heat

2.3.1 Industrial processes

To determine available industrial waste heat in 2050, the transformation of industry in terms of production volumes and innovative processes from [20] is taken into account, reflecting a 95% CO_2 reduction scenario. Industrial excess heat potentials consider the transformation of industrial processes to a climate-neutral economy and thus calculate the excess heat available in 2050. This assumption reduces the available potentials as on the one hand, energy efficiency potentials are exploited, and on the other hand, reduced production volumes are projected due to material efficiency. Furthermore, in the case of electrified furnaces or hydrogen-based steel making, the process efficiency is higher than the conventional process based on fossil fuels.

The location of industrial sites are assumed to remain where there are today, and the ISI Industrial Database [21], published in the Pan European Thermal Atlas 5 [11], is used. The methodology to estimate excess heat potentials based on production is introduced in [1]. For this study, the values where adapted to include new processes like hydrogen-based steelmaking and petrochemical products.

The flow temperature of DH systems influences the energy that is available at industrial sites. Hence, it was varied from 95°C, 55°C to 25°C. The maximum distance is assumed to be 20 km, as individual sites could have high potentials and a long distance could be feasible.

2.3.2 Waste incineration

The potential excess heat was calculated in the project Heat Roadmap Europe 4 [22] and published in the Pan European Thermal Atlas 5 [11] as shapefile. The data for this study were taken without changes. For further information on methodology and input data, the reader is referred to [22]. The maximum distance for waste incineration plants to DH areas was assumed to be 10 km.

2.4 Heat pumps

2.4.1 River and water heat pumps

Heat from river and water sources can be an interesting heat source for heat pumps. Studies [23–25] come to the conclusion, that there is a vast potential to be exploited, even though temperatures in winter are quite low (average 2°C - 8°C). The input data for river location and monthly average flow rates were taken from Copernicus Climate Change Service Information [12]. River locations were filtered out that show less than 20, 30 or 40 m³/s as an average winter flow rate, as it is assumed to be too small. The minimum flow rate should be assessed with the Q95 value, meaning that in 95% of time this flow should be available, being at least 4 m³/s [23]. It could be shown, that in winter months the Q95 value is sometimes half of the average value [26]. Thus minimum monthly values of 20 m³/s were assumed, as smaller rivers have often not sufficient temperatures in winter. As empirical data for the technical potential are limited, the minimum value was varied.

The rivers and lakes were grouped into areas that have a great potentials, with flow rates above 100 m³/s, and areas that have medium to small potential below that threshold. From this, typical projects and studies like [23,24] were taken to define mean values for typical power (80 MW for smaller flow rates and 150 MW for higher flow rates) that river heat pumps can generate. With assumed full load hours of 2000h for smaller projects (lower flow rates have generally lower temperatures) and 3000h for bigger projects the average potentials for river heat pumps are generated. The maximum distance to DH areas is 5 km and minimum distance between two extraction points at the river is 10 km.

2.4.2 Waste water treatment plants

The locations of waste water treatment plants are taken from Hotmaps [13,27], where the plants are published with the maximum energy that is available in the waste water. In the Pan European Thermal Atlas 5 [11], taken from ReUseHeat [28], excess heat from waste water treatment plants with similar locations is also published, but without Switzerland and Norway. For this study, the locations and power was taken from Hotmaps, but typical full load hours of 2241h were derived with the values from ReUseHeat.

3 Results

3.1 Technical potentials

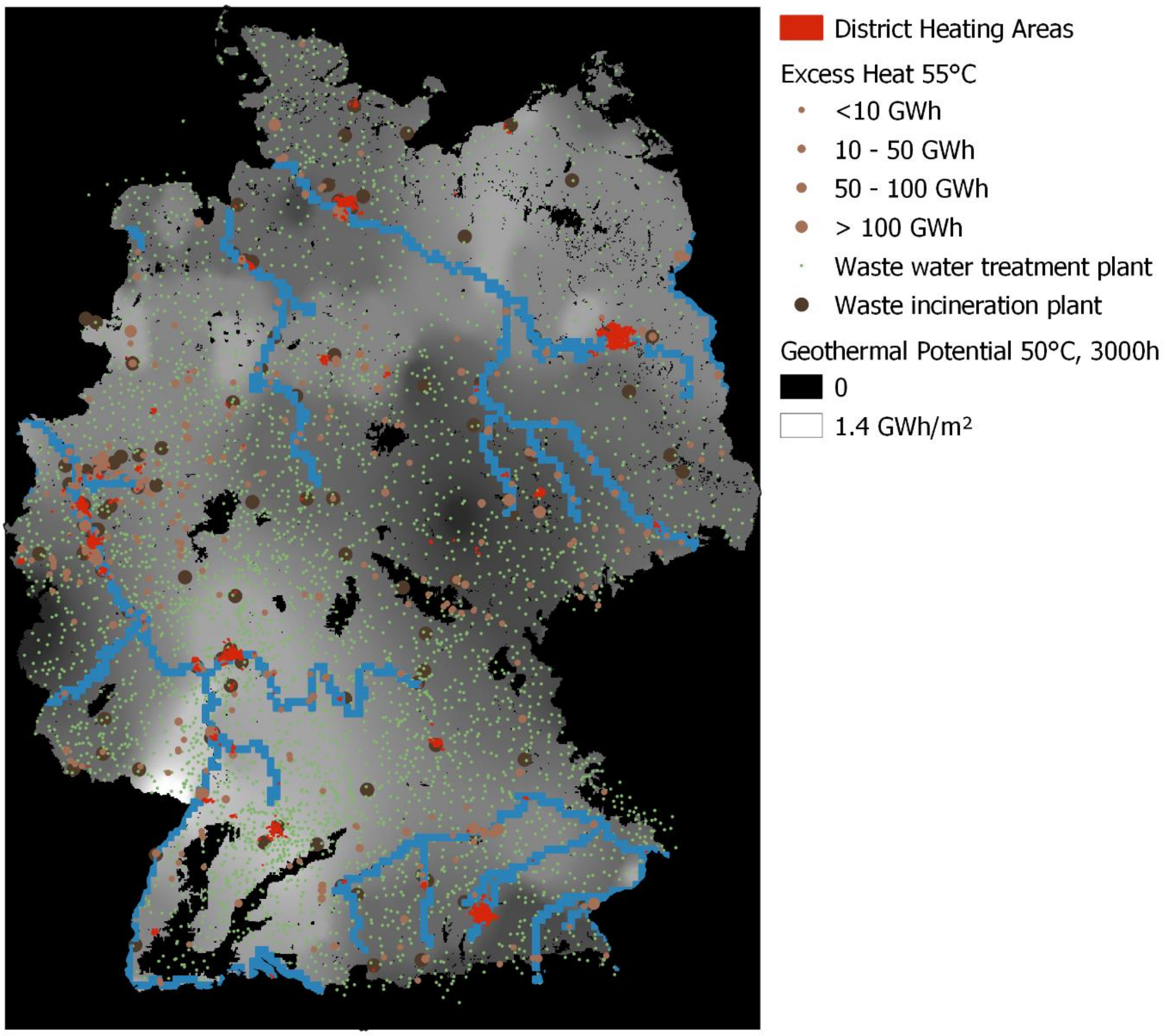

Figure 1: DH areas and potentials investigated in this study: industrial excess heat, waste water treatment plants, waste incineration plants, geothermal potential and rivers (blue) in Germany

In Figure 1, all the technical potentials and DH areas for Germany are depicted. In total, the DH demand in 2050 is modelled to be 30,420 GWh for Germany, which is rather low compared to other studies analysing the DH demand in 2050 [3,29]. In Table 2, the potential ranges are shown. The supply potential is the total potential in Germany, irrespective of spatial location to DH areas. The range considers the different assumptions on the technical potentials of geothermal, industrial excess heat and rivers potentials, as explained in chapter 2. The demand potential considers to what extent the available heat potentials can be utilized in the modelled DH areas. It considers the maximum distance of the sources to the areas of DH demand, analysed with distance analysis in GIS. If the potential is higher than the demand, the value of the demand potential is set to the value of the demand.

Table 2: Technical supply and demand potential for heat generation potentials in Germany

Heat Generation Potential	Range of annual supply potential	Range of annual demand potential
Geothermal	171,105 - 376,996 GWh	12,658 - 17,929 GWh
Industrial excess heat	4438 - 24,680 GWh	2178 - 4758 GWh
Waste incineration	45,699 GWh	12,757 GWh
Rivers and lakes with heat pump	293,046 - 348,208 GWh	9,909 - 11,204 GWh
Waste water treatment with heat pump	648,524 GWh	5143 GWh

In total, only the two biggest DH areas in terms of DH demand cannot be supplied by the total of the considered technical potentials. Please note, that solar thermal and biomass potentials were not included in this calculation and can possibly contribute a considerable share of heat to DH systems. Generally, geothermal potentials show the highest demand potentials, with corresponding high supply potentials. It needs to be considered, that the geothermal potentials are petrothermal potentials that were not yet economically exploited. Hence, the future economic potential is uncertain and needs be further evaluated. Waste water treatment plants show the highest supply potential from all sources. Hence, such plants could to be an underestimated source of heat for future DH systems, just due to the high number of existing plants. As they need to be in close vicinity to DH areas, the demand potential is reduced to only about 5000 TWh and could be increased with a higher extend of Dh areas. Waste incineration plants show also considerable high amount of supply and demand potentials, and are located often close to larger cities. Future industrial excess heat is reduced in comparison with today's estimations due to new production routes and high efficiency in the production. Hence, the industrial excess heat shows the lowest potential. However, as available excess heat is often concentrated at larger, energy-intensive industrial sites, they can have high potentials for individual DH areas.

Geothermal potentials were analysed by Umweltbundesamt in 2018 with a similar methodology [18]. They assumed 2500 full load hours, and a depth of 3000m. The resulting petrothermal potential is 214 - 478 TWh/a depending on different assumptions on availability on land and temperatures of T_2=65°C - 35°C. The potential in this study of 171 - 377 TWh is within the range and comparable.

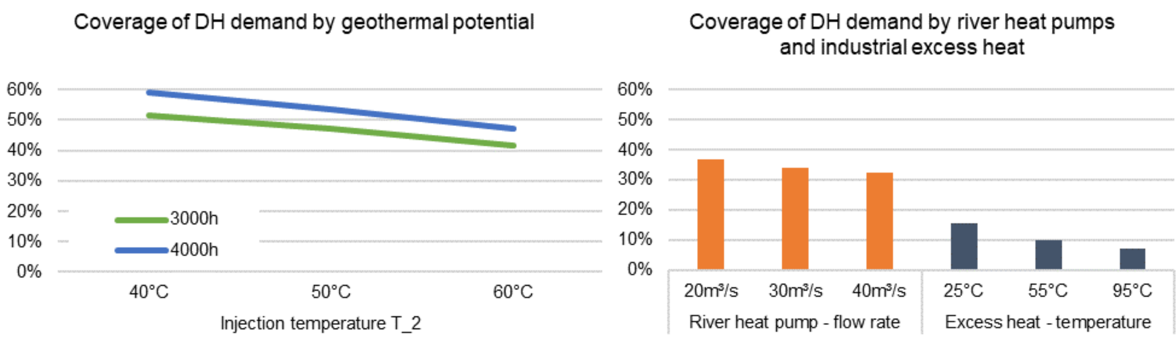

Figure 2: Coverage variation by geothermal potential (left), river heat pump and industrial excess heat potentials (right) depending on varied parameters

In Figure 2, the coverage of the demand by the different potentials are shown. The focus of this analysis is the range of the variation, based on the different assumptions for each of the analysed technology. On the left, the variation of geothermal potential is shown, depending on the assumption of injection temperature and full load hours. In total, the DH demand of the DH areas could be supplied by geothermal energy by 42% up to 59%. The assumption of higher full load hours leads to an increase of 14% of the available potential, while reduction of the injection temperature and thus the temperature in the DH system by 10K leads to an increase of more than 10% of the coverage. On the right, the variation for river heat pumps and industrial excess heat potentials are depicted. The variation of the minimum monthly flow rate of rivers of 20, 30 and 40 m³/s leads to a decrease of the coverage from 37% to 33%. The decrease of temperature level on which industrial excess heat is utilized from 95°C to 25°C more than doubles the available heat from industrial plants for DH areas, the coverage increases from 7% to 16%.

For following analyses, following assumptions were chosen: for geothermal energy 50°C injection temperature and 3000 full load hours (see [18]), for industrial excess heat 55°C temperature level (see [1]) and for river heat pumps the lowest value of 20 m³/s minimum river flow rate (see [23,26]).

3.2 Cluster analysis

To present the results and the outlook, the individual DH areas were grouped using an agglomerative clustering algorithm provided by the Python package SciPy (similar to [30]). In agglomerative clustering, the algorithm calculates the dissimilarity between all elements and gradually combines two elements with the least dissimilarity into a cluster. This formed cluster is then used again in the next iteration. Various schemes for the dissimilarity calculation and linkage types are available. We used ward's minimum variance method and the Euclidean distance. Key input figures for the clustering analysis where the heat demand in the individual DH areas and the percentage coverage of the heat demand with different heat sources (see also section 2). In order to minimize the effect of different orders of magnitudes (especially between demand and coverage), the figures were scaled with a min-max scaler, resulting in figures between 0 and 1.

The endpoint or terminus of the hierarchical clustering algorithm can be freely chosen. A so called dendrogram, showing the pairwise combinations, can be used to select an appropriate terminus. The dendrogram of the clustering performed in this paper is shown in Figure 3. A terminus of 2.5 was chosen, resulting in six different clusters (see red line in Figure 3).

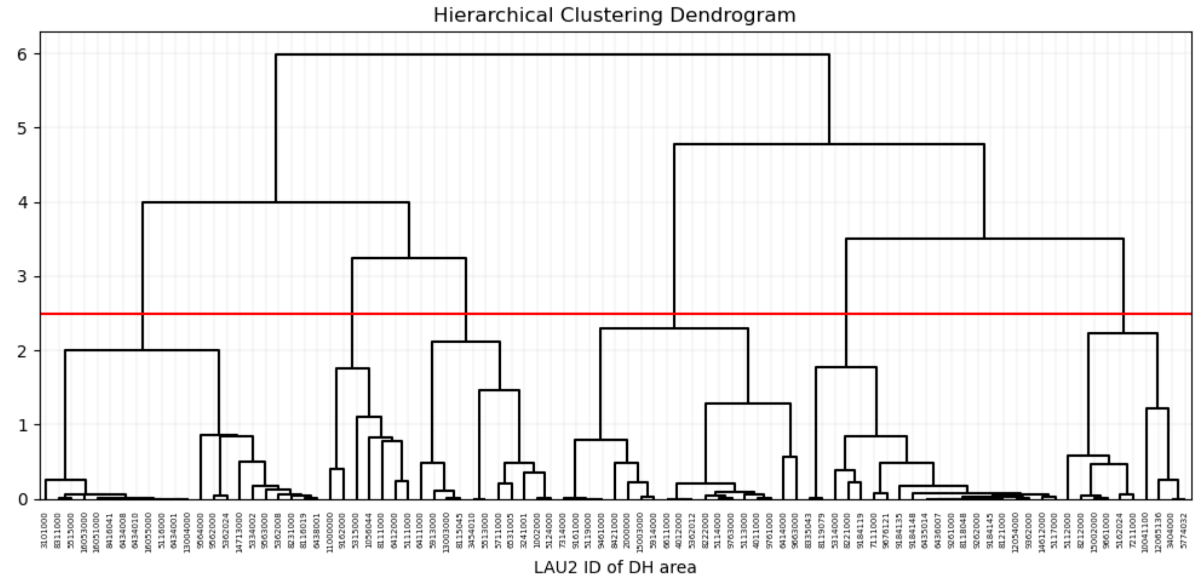

Figure 3: Hierarchical cluster dendrogram; red line indicates terminus, i.e. number of clusters

The resulting six clusters differ in size and available heat sources (see Table 3 and Figure 4). Overall, all clusters have a high potential for geothermal energy coverage of the heat demand in 2050. Thereby, cluster 1 represents medium size DH areas where geothermal energy could deliver on average up to 97% of the heat demand. At the same time, waste to energy plants could cover up to 30% of the heat demand. Cluster 2 depict the largest DH areas with heat demands on average of almost 3000 GWh (10% of total DH demand). Thereby, cluster 2 shows the lowest potential for geothermal energy coverage. The generation profile in the DH areas could be more mixed with an average coverage from waste incineration of more than 50%. Cluster 3 also shows a high share of waste heat incineration coverage, while cluster 4 has a high potential to integrate heat from rivers (with heat pumps). Cluster 5 represents smaller DH areas where most heat could be provided by geothermal energy or by rivers. Cluster 6 includes the smallest DH areas with the highest potential of excess heat coverage.

Table 3: Mean expressions of the clusters when six clusters are selected for 89 DH areas in Germany in 2050

Cluster	Number of DH areas	Mean DH demand [GWh]	Mean geothermal coverage [%]	Mean waste water coverage [%]	Mean waste incineration coverage [%]	Mean excess heat coverage [%]	Mean heat from river coverage [%]
1	22	142	97%	28%	2%	2%	0%
2	7	2971	19%	19%	58%	10%	46%
3	11	151	100%	35%	98%	25%	0%
4	19	143	100%	7%	99%	37%	100%
5	20	72	100%	16%	2%	3%	100%
6	10	69	100%	14%	0%	91%	60%

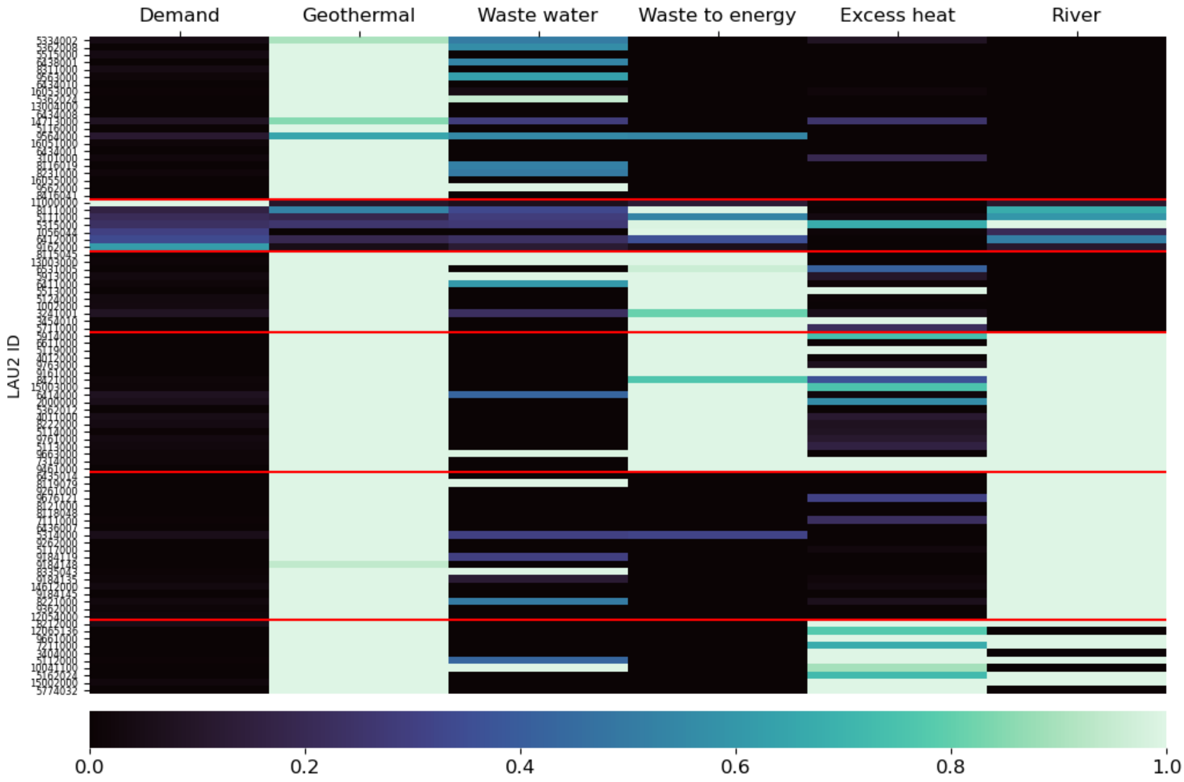

Figure 4: Heatmap of (scaled) key figures of the 89 DH areas in Germany (red lines indicate cluster)

The results of the cluster analysis can be used in particular to carry out future modelling of DH areas. Specific transformation paths can be derived for the clusters and thus the complexity of energy system models can be reduced.

4 Conclusions and Outlook

In this analysis, the potential generation of DH by renewable and excess heat sources in the future is estimated for Germany. First, possible DH areas and the DH demand for 2050 are modelled. As a second step, technical potentials from different sources were calculated and mapped. In this step, the most uncertain parameters in the calculation were varied. As a third step, a distance analysis was conducted, adding up all the potentials lying within a certain distance to the border of the DH areas. It can be shown, that almost all DH areas can be completely supplied with the considered technical potentials. An economic analysis is needed to reflect on the fixed and variable costs of these technologies. Solar thermal and biomass potentials were not considered in this analysis, as it was assumed that the availability is not spatially limited, however it needs to be included in an economic analysis.

The variation of the potentials for the use of renewable heat sources and waste heat shows that the assumptions on geothermal potentials have the greatest influence on the coverage of demand. Also, the assumption on the temperature level of excess heat has a considerable influence. The variation of the minimum flow rate of rivers does not a show significant influence.

In summary, the sensitivity analysis shows that different technical assumptions have a medium impact on the results on a possible supply of future DH systems. The assumptions on maximum distances were not varied. In an economic analysis for individual grids, the maximum distance should take into account the individual energy amounts of the source.

The mapping of individual DH areas in Germany with available heat sources in 2050 was based on annual values, with full load hours representing the seasonal availability. However, the use of large heat pumps using the ambient temperature or peak load boilers operated with electricity, biomass or synthetic gases such as hydrogen or methane seems unavoidable to cover load peaks and winter demand, which cannot be represented by the analysis based on annual or seasonal data.

This analysis from a system perspective does not allow to take into account all regional parameters and different system designs and optimizations. The aim is to evaluate DH generation potentials in the future and can hint regional planners to the most important sources.

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