International Journal of Sustainable Energy Planning and Management Vol. 40 2024 124–137

International Journal of
Sustainable Energy Planning and Management

Identifying future district heating potentials in germany: a study using empirical insights and distribution cost analysis

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ABSTRACT

District heating will play an important role in the transition towards climate-neutral heating. Various studies on modelling the energy system show that district heating and the related expansion of the networks can have different levels of importance. A main reason is that the costs for distribution grid expansion are not well or not at all considered and empirical evidence for a threshold for cost-effective distribution costs is missing in such studies. In this paper, we aim to improve empirical evidence allowing to improve the representation of future district heating expansion in energy systems models. For that, the current status of district heating is analysed in high spatial resolution for Germany. The results show that with the currently accepted average costs, a large range of the possible future market share of district heating for buildings between 17–52% is possible by 2050, with the parameters of the connection rate and the renovation rate of the building stock. We conclude that the district heating share could be increased by the factor of 2 to 5 in the future, proving the importance of climate-neutral district heating in the transition.

Keywords

District heating;
Heat density;
Distribution capital cost;
Geographic information system;
Economic potential

http://doi.org/10.54337/ijsepm.8142

1. Introduction

In recent years, the imperative to achieve climate-neutral heating has become a focus of political debate in Germany and the EU. District Heating (DH) could be a decisive factor in this transition, which is at the centre of the discourse on heat planning. DH has numerous advantages, including the utilization of multiple renewable heat sources, the ability to balance peak demands through heat storage and the cost advantages due to economies of scale [1]. However, the inherent challenge lies in the need for an infrastructure for heat transportation and distribution to the consumers. Distribution capital costs are largely dependent on local conditions and defined as the specific annualized capital costs needed to build the DH distribution grid, per heat quantity delivered. They are an additional cost component on top of the heat generation costs for DH besides further costs for transport and service pipes [2]. Lower distribution costs occur in areas with higher heat densities, i.e. the heating demand per specific area, thus possibly making DH cost-competitive to individual heating solutions. The analysis of potential DH areas on the country-level is therefore intricately linked to local conditions. Existing scenarios of energy system studies present the role of DH as varying in importance by 2050 [3]. This variability implies a broad spectrum of economic possibilities of DH in competition with decentral heating options as well as thermal building renovation. Achieving reliable modelling results for the identification of

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cost-optimal pathways requires the integration of empirical parameters in the modelling process. Analysing the empirical correlation between heat densities, derived distribution capital costs and their respective DH installations provides valuable insights into the potential DH deployment in the future.

1.1 State of research

Empirical analyses for the current state of DH on the country-level have been conducted before, e.g. for Germany, Triebs et al., 2021 [4] analysed the fuel input on the network level, and Weinand et al., 2019 [5] published an open dataset on the share of buildings with DH for the municipalities based on the census 2011. However, only a few studies have analysed the current spatial extension of DH on the country- or EU-level, mostly due to lack of data. In the Pan-European Thermal Atlas [6], current DH areas are published as shapefiles in an online map application, together with the heating demand. The dataset is derived from a database of DH systems on the city-level based on manual research, with the spatial extension derived from areas with high heat densities [7]. Pelda et al., 2021 [8] developed a district heating atlas comprising 50% of the DH demand of Germany, which is published in an online map [9]. It is based on the census 2011 combined with research on the website of operators, and contains several key indicators about current DH systems on the city scale. In summary, the datasets on existing DH areas with a large geographical extent are available with the spatial resolution of cities. However, higher resolution (i.e. hectare-level) is needed for an empirical analysis of the correlation with distribution capital costs.

Several studies have calculated heat density and derived distribution capital costs for DH with high spatial resolution on a large scale with the aim to identify future DH potential areas. The heat density can be expressed in two different ways. On the one hand as linear heat density which is the ratio between delivered heat and DH grid length. On the other hand as (areal) heat density, which is the delivered heat per hectare of space. This is useful if a grid does not yet exist or data availability on grid lengths is scarce. This approach uses the effective width concept to derive the linear heat density from the heat density analytically based on an empirical correlation. It was first introduced by Persson and Werner, 2011 [2], refined by Persson et al., 2019 and 2021 [10, 11], as well as analysed in a parameter study in García et al, 2023 [12]. It was applied with different parameters and compared to a more data-intensive optimization method on the city-level for Vienna and Brasov, as well as applied for EU-27 in Fallahnejad et al., 2018, 2021 and 2024 [13–15]. In the project Heat Roadmap Europe, the current DH areas from peta [6] are used to identify possible extensions with an analysis of cost-effective heat densities on the EU-level [16]. Leurent, 2019 [17] analysed the DH potential in France with a spatial approach, by assuming a threshold value for the calculated linear heat density as the upper limit for economical grids. On the local scale, Dochev et al., 2018 [18] used the linear heat densities to assess the DH potential of Hamburg, again with an assumed threshold value as the upper limit. For Germany, Blömer et al., 2019 [19] calculate capital costs in €/m, using a cost threshold value to identify potential areas. In summary, an empirical data analysis considering the correlation between heat density, distribution capital cost threshold and existing DH on the hectare-level is absent in the existing body of research. Instead, assumed thresholds are derived from typical values in highly populated areas and cities to identify potential DH areas in the future, reflecting a normative approach. With empirical data on accepted costs, the economic decisions can be integrated into models.

In energy system studies on the national or EU-level, DH is part of the solution for the heating transition, however often represented with a low modelling resolution. Manz et al., 2022 [3] compare energy system studies with regard to the resulting DH market share. The range for Germany is between 13% and 37%, leaving a broad range for the role of DH in the heating transition. The assumed threshold values for economic future DH areas influence the resulting DH potential and market share and thus, should be proven by empirics. The future role of DH based on empirical cost thresholds has not yet been quantified in models. Therefore, we analyse the empirical DH costs in Germany, and conduct a scenario analysis to improve the accuracy of modelling the possible future role of DH.

1.2 Research objective

The objective of this study is to address three main research questions, aiming to fill data gaps in the literature by establishing an empirical correlation between existing DH and accepted distribution capital costs, which facilitates a robust scenario analysis of the potential future of DH in Germany:

- What is the status quo of DH areas and demand?

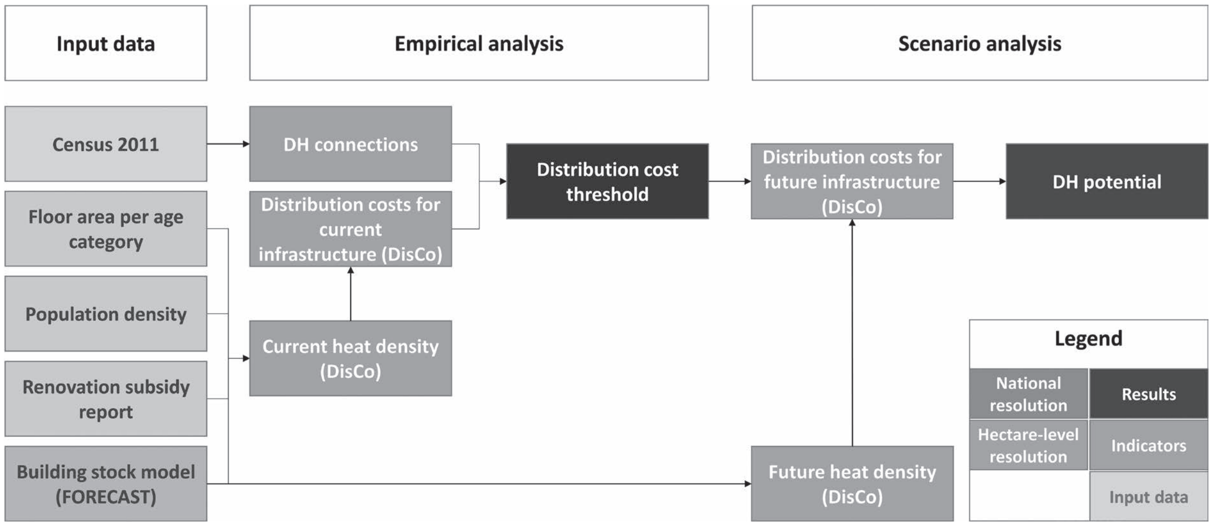

Figure 1: Data processing and methodological steps applied in the paper.

- What is the empirical correlation between the existing DH infrastructure, heat density and distribution capital costs?
- Where are future DH potentials, considering the existing DH areas and thermal building renovation activity until 2050?

To answer these questions, first, different data sources with a high spatial resolution are combined to analyse the status quo of DH and calculate the heat density, deriving distribution capital costs and analyse the correlation. The influence of the different historical development in West and East Germany in the last century on the correlation is investigated. As a second step, the empirical distribution capital cost threshold is applied to estimate the future potential DH market share in a scenario analysis. The structure of the paper is as follows: In Chapter 2, we describe the datasets used and the methods applied. In Chapter 3, we present the results for the current status of DH, the correlation to distribution capital costs and for DH potentials. We then discuss the results and show the limitations in the approach. Finally, in Chapter 4, we conclude the analysis.

2. Data and method

Several datasets on the hectare-level of the building stock and DH were combined in this study. Heat density, commonly in GJ/hectare or kWh/m², includes the annual demand for space heating and sanitary hot water for both residential and tertiary buildings. The DH market share is defined as the share of energy demand for heating and sanitary hot water in the buildings sector that is covered by DH. The connection rate is defined as the share of connected dwellings to DH compared to the total number of dwellings within a DH area. The empirical analysis of the status quo and current DH distribution capital costs is based on calculated heat density and DH connections in Germany. For the future development, we applied a model-based approach with a soft-coupling of a building stock model (FORECAST) and a spatial model (DisCo). In Figure 1, an overview of the data sources and processing as well as the methodological steps is shown, which are described in detail in the following.

2.1 Data processing

As shown in Figure 1, different datasets were used to derive: (1) the current DH status and (2) the current and future heat density and the distribution capital costs, both on the hectare-level for the geographical scope of Germany. The data source for identifying the current DH extension is the European-wide census, whose results were published for Germany on a 100m x 100m grid (hectare-level) [20]. As the dataset is based on the last census, the data are from the year 2011, published in the year 2017. More recent data of the subsequent EU-census 2021 are currently being processed by the statistical offices. Integrating more recent data into the analysis could lead to more accurate thresholds, however, as DH installations are built over a long time horizon, the difference is possibly negligible. In our analysis we used the dataset that lists for each hectare the number of dwellings per type of heating (DH and others), totalling to 2.7 million hectare cells in Germany with at least one dwelling. From that, we applied data validation steps as well as neighbour analysis to identify errors in the dataset which stem mainly from people who answered incorrectly in the questionnaire about their type of heating. For that, all cells with less than 100 DH connections in a radius of 3 km are filtered out. Another criterion was applied to filter small building networks, so that only networks with more than 10 DH connections of their own and more than 1000 DH connections in a radius of 3 km are considered as DH networks. After the data processing steps, the dataset comprises 133,348 cells with DH connections.

The heating demand of buildings and thus the heat density depends mainly on the heated floor area per hectare, the building type (single-/multi-family or non-residential house), the year of construction and the renovation status. The main data source for the calculation of the heat density was the Hotmaps dataset, publishing the floor area per building age category on the hectare-level [21]. In this dataset, four age categories are used. The age categories needed to be harmonized with statistical values. The base year for this dataset is 2012, with no updates available, which aligns with the census data from 2011. Further data needed to estimate the regional heat density is the population density on the hectare-level, to differentiate areas with single-family houses (SFH) and areas with multi-family houses (MFH) that are typically more densely populated. These data were also taken from Hotmaps [21]. Additionally, the regional renovation activity was derived from the subsidy reports on the NUTS 3 level of the German state-owned bank Kreditanstalt für Wiederaufbau (KfW) that gives out loans and subsidies for building renovations [22–27]. The sum of loans for refurbishment from the available years 2015 until 2020 was used to derive regional indicators for the renovation activity and to distribute renovated buildings across the regions.

The energy demand simulation model platform FORECAST [28] was used to model the building stock for the current (2012 and 2020) and future years (2030 and 2050). The model FORECAST-Buildings, which has been applied in several EU-wide analyses, e.g. [29–31], uses an extensive building stock database and models the useful and final energy demand for both residential and tertiary (non-residential) buildings in a high technological resolution. The results were calibrated for statistical years until 2020 and future renovation activity and choice of heating technology is modelled endogenously. The temporal resolution is annual and the spatial resolution is national. The results are disaggregated to the hectare-level in a downstream model DisCo [32], with a soft-coupling via a common SQLite database, where the results of FORECAST are stored and further processed in DisCo. The model DisCo is a Python-based model, which uses the instance of QGIS together with GDAL libraries to perform spatial computations. From FORECAST-Buildings, two input datasets are used as an input for the regional disaggregation in DisCo:

- the total floor area in m² in Germany and
- the specific useful energy demand for heating and hot water in GJ/m².

These parameters are given in the model database per building category, which means:

- per building age class,
- building type (single-/ multi-family or non-residential house) and
- renovation status.

In the model DisCo, first, the floor area per building category is distributed to the hectare-level. For that, the floor are per age class on the hectare-level from Hotmaps is used, and, for residential buildings, split up for each hectare into SFH and MFH depending on the population density. Further, renovated floor areas are distributed to hectare level, with higher shares in regions where the subsidies are comparatively high. As a second step in DisCo, the useful energy demand is calculated on the hectare-level by multiplying the national average of specific useful energy demand in GJ/m² with the floor area on hectare level per building category.

2.2 Spatial analysis

In this chapter, the spatial analysis is described as a three-step approach. First, the current heat density is calibrated and matched with the statistical data on DH installations. Second, current distribution capital costs are derived from that matching and an empirical correlation is investigated between the distribution capital costs and the resulting DH installations. Third, a scenario analysis is conducted, based on two different ambition levels of building renovation. Based on the future useful energy demand and thus reduced heat density, future distribution capital costs are derived and DH potential areas are identified. The spatial analysis was conducted in QGIS and the plugin PyQGIS [33] to map and process the raster datasets.

2.2.1 Matching DH installations with heat density

The aim of this step is to combine the datasets of the heating demand with DH installations on the hectare-level in QGIS. The resulting raster dataset contains the heat density, the number of dwellings and the number of dwellings with a DH installation. The validation of the derived heat density is conducted on the national level for the base year 2012, using the results of FORECAST-Buildings that includes an extensive statistical database. The DH installation numbers are used further to derive average DH connection rates within one DH area.

2.2.2 Distribution capital costs

In this step, distribution capital costs are calculated based on the heat density. This is conducted first for the existing DH areas, and later for the possible DH areas in the scenario years. The aim here is to identify parameters from the existing areas that can be projected to the future, with the rational that current accepted costs can be assumed to be accepted in the future. The method to calculate the distribution capital costs in C_d €/GJ is based on Persson & Werner, 2011 [2], using the updated parameters from Persson et al., 2019 [10] and 2021 [11]. As stated in these sources, these cost parameters can be used as a proxy for future low-temperature grids (4th and 5th generation DH [34]) as well. It represents the annualized investment for the distribution pipes and is dependent on the heat density q_L [GJ/m²], referring to the sold heat in this case, in the denominator. Further parameters are the average pipe diameter d_a as a function of the heat density, the effective width w as a function of the plot ratio $pr = \frac{A_B}{A_L}$ (ratio of building floor area per given land area), the annuity factor a and the cost constants C_1 in €/m and C_2 in €/m²:

$$C_d = \frac{a \cdot \left(C_1 + C_2 \cdot d_a\right)}{q_L \cdot w} \text{ [€/GJ], with} \tag{1}$$

$d_a = 0.02\ m$ for $(q_L \cdot w) \leq 1.5\ GJ/m$;

$d_a = 0.0486 \cdot \ln\left(q_L \cdot w\right) + 0.0007\left[m\right]$ for $(q_L \cdot w) > 1.5\ GJ/m$, and (2)

$w = \frac{e^2}{pr}\left[m\right]$ for $pr \leq 0.12$;

$w = 55\ m$ for $pr > 0.12$. (3)

2.2.3 Scenario analysis

The scenario analysis uses the projection of the building stock until the year 2050, with two scenarios differing by their refurbishment ambition levels, called *high-refurb* and *low-refurb*, based on the project Paris Reinforce [35]. With these two scenarios, the influence of a lower heat density on the distribution capital costs can be assessed. The model chain of the national simulation of the building stock in FORECAST-Buildings and the downstream regionalization of floor area and useful energy demand on the hectare-level in DisCo is applied and analysed for the years 2020, 2030 and 2050. The derived heat density serves as a base for the calculation of future distribution capital costs, depending on renovation and connection rates. It is assumed that the existing infrastructure will not need to be replaced and the current costs are depreciated, thus these costs are subtracted from the future distribution capital costs for each cell. Only for densification, costs are calculated as additional expenditures to add pipes or increase the diameter. The aim is to identify future potential DH areas with comparable distribution capital costs as the current DH structure on the hectare-level. The main parameters in this analysis are the renovation ambition, reflected by two scenarios, and the connection rate and the DH market share that are varied.

The renovation activity of individual building components are triggered by their technical lifetimes. The two scenarios *high-refurb* and *low-refurb* assume different mean values for the distribution of the technical lifetime of building components. This results in an average annual renovation rate (renovated floor area divided by total floor area) of 1.6% and 1.3% between 2020 and 2050 in the *high-refurb* and *low-refurb* scenario, respectively. By 2050, in comparison to 2012, the total useful energy demand decreases by 39% in the *high-refurb*, and by 32% in the *low-refurb* scenario.

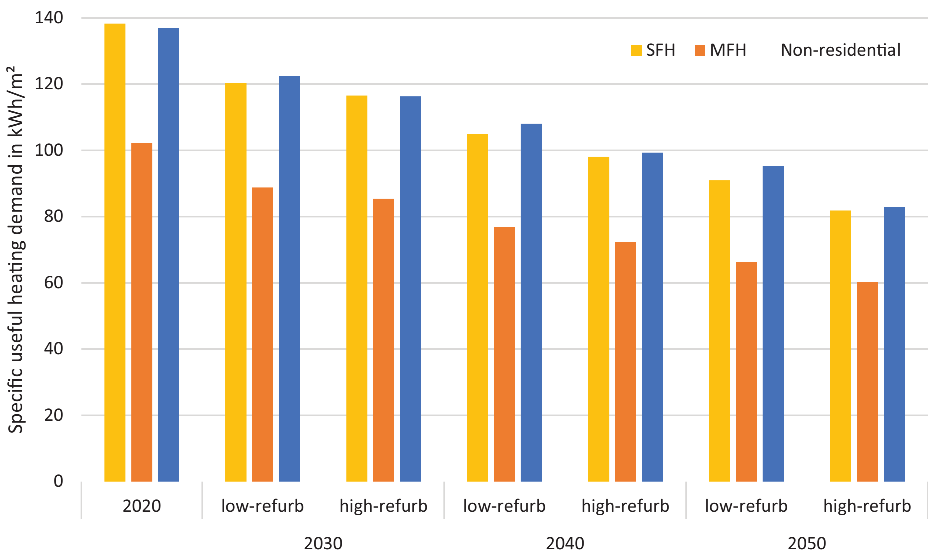

Figure 2: Specific useful energy demand per building type as modelling result from FORECAST-Buildings, for the two renovation scenarios.

The reduction in the average specific useful heating demand of the different building types is depicted in absolute values in Figure 2. It varies from 32% in non-residential buildings to 37% in SFH buildings and 39% in MFH buildings in the *low-refurb* scenario and goes up to 40% in non-residential buildings and to around 43% in residential buildings in the *high-refurb* scenario.

3. Results

In the following, the resulting status quo of DH, the correlation with distribution capital costs and the future DH potential for Germany are presented. Each of the results is based on the hectare-level resolution.

3.1 Status quo of DH

The census dataset indicates that DH is often installed in city centres. In Figure 3, the number of connections is shown. The plotted census data have a similar extension as the network from DH operators that publish maps of their grid online (e.g. the city of Karlsruhe), indicating that the filter criteria are sufficient to capture errors and outliers. The connection rate for each DH area can be calculated by dividing the number of dwellings that are connected to DH divided by the total number of dwellings. The highest connection rate is identified to be in Flensburg, with an average value of 91.5%.

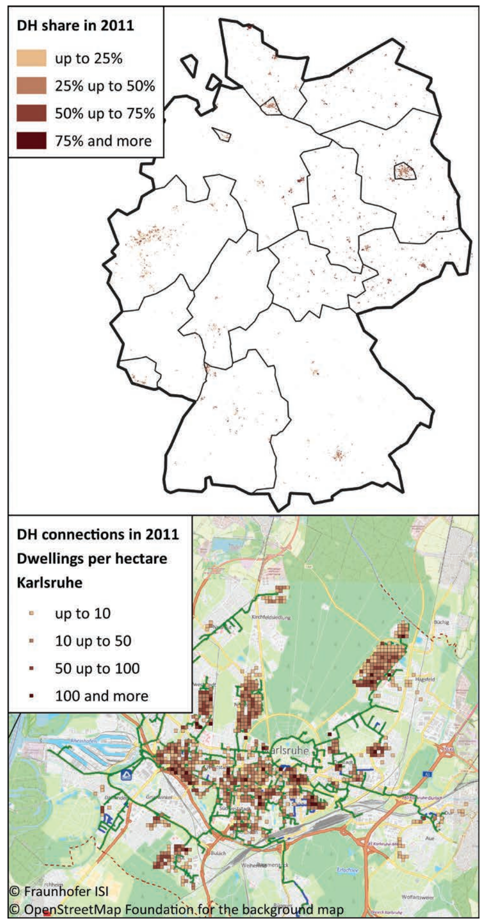

Figure 3: Visualisation of the census 2011 dataset after data processing steps, showing the number of DH connections per hectare, visualized overlaid with the DH network map of Karlsruhe in 2021, published in [36].

3.2 Correlation of existing DH, heat density and distribution capital costs

The spatial matching of the current DH installations and the heat density aims to derive accepted distribution capital costs. The calculated current heat density is depicted in Figure 4. The heating demand covered by district heating was calculated by multiplying the derived connection rate with the respective heating demand of the covered cell. The aggregated annual useful heating demand covered by DH sums up to 199 PJ, in line with the statistics [37].

The resulting raster dataset from the spatial matching includes for each hectare cell the heat density, the number of DH connected dwellings and the total number of dwellings. This dataset was post-processed in python, to group the cells by the heat density in different classes. For each heat density class, the number of cells in that class as well as the share of cells that have at least one DH connection is calculated (Figure 5).

In Figure 5, it can be observed that with higher heat densities the share of cells that have a DH connection increases. Please note, that the number of cells in the heat density class 100 GJ/ha exceeds the axis limit and adds up to 1.2 million. The range of heat densities between 800 and 1700 GJ/ha includes the centre of villages and also most parts of a city, however without the most densely populated areas. Heat density values above 1700 GJ/ha thus represent mostly city centres. In areas with very high heat densities 70% of the cells have DH access, but there are not many areas with these high heat

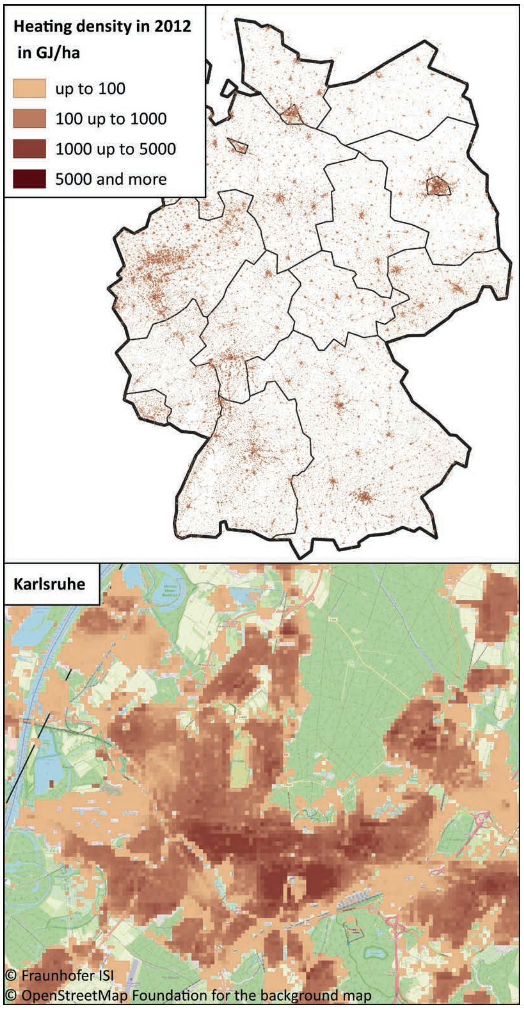

Figure 4: Calculated heat density in GJ/hectare in the base year.

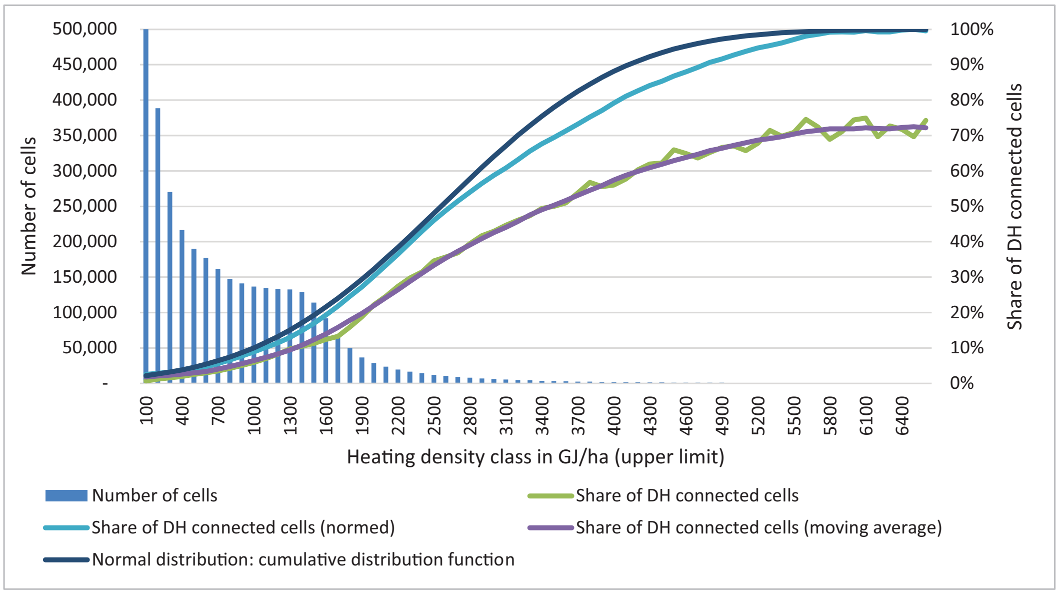

Figure 5: Number of cells per heat density class and share of these cells that are connected to DH in Germany in the census 2011 dataset, together with a normal distribution fit.

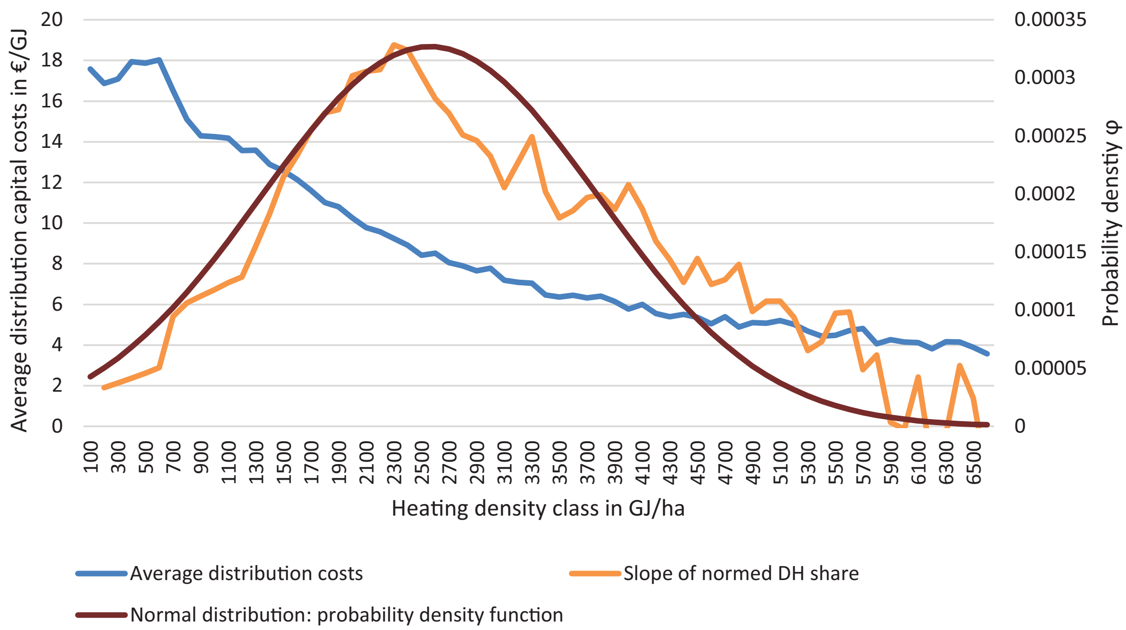

Figure 6: Average distribution capital costs for the census data, normal distribution density function and fit to slope of DH share.

densities. However, a significant share of cells with low heat densities have DH connections, mainly those that are close to larger cities with an existent DH system. From this comparison, no clear threshold of an economic heat density can be derived. The share of DH connected cells was additionally standardized as 100% (representing the maximum), to enable the fitting to a normal distribution.

Plotting the slope of this function, a normally distributed shape of the share of DH connected cells can be fitted over the heat density (Figure 6). The expectation value is 2560 GJ/ha, signifying the value where the probability for a DH connection is 50% of the maximum value. This could be used as the threshold value for an economic value for DH installations. Even though the value of 2560 GJ/ha is in the lower range of possible heat density values, it represents already densely populated cities (compare Figure 4). Additionally, the distribution capital costs for the heat density of 2560 GJ/ha are in the range of 8.5 €/GJ, reflecting the accepted costs for DH infrastructure on average. Weighting this value with the amount of heat sold in each cell, the average distribution capital costs decrease to 6.14 €/GJ. The normal distribution shows different values when investigated separately for West and East Germany, which is due to the separation and different situation in the two states of Germany in the last century. This shows the impact of different developments in the heat infrastructure over the last century, when Germany was divided into two countries.

Table 1: Parameters derived from the fit of the normal distribution of DH connected cells in census 2011 dataset.

Statistical value	Germany	West Germany	East Germany
Expectation value μ	2560 GJ/ha	2789 GJ/ha	1685 GJ/ha
Standard deviation σ	1220 GJ/ha	1230 GJ/ha	773 GJ/ha

The statistical values to describe the fit of the normal distribution are listed in Table 1 for Germany, and separately for West and East Germany. The expectation value is significantly lower in the Eastern part, with a lower variance and a higher share of DH connected cells, indicates that more DH grids have been built in East Germany while accepting higher distribution costs.

3.3 Future DH potentials

As derived from the results in section 3.2, today's average share of DH in areas with high heat densities is about 70%. The obvious strategy would be to install DH in all city centres. However, the question arises to what extent DH could be expanded and newly built, starting from the current level. The distribution capital costs for future densification of existing networks as well as new construction are calculated based on the future heating density (Figure 7). The connection rate and the renovation of buildings are varied. The marginal costs do not change when the existing infrastructure is included in the modelling, however, the average distribution capital costs decrease by about 1 €/GJ.

In general, the lowest distribution capital costs are present in cities and areas with very high heat density where no DH is currently existent, as well as in areas with currently low connection rates within areas with DH. The current average distribution capital costs of 6.14 €/GJ serve as a basis for identifying future DH economic areas. The DH market share in Germany in the year 2021 was 9.2% [38] and the average connection rate was 59% in 2011, which was derived from the census data set. In Figure 8, the average distribution capital costs in 2050 for different building thermal renovation ambition levels, connection rates (DH share within DH area) and the DH market share (share of heat supplied by DH) are shown.

With increasing market shares the average distribution costs increase, as more expensive cells are connected. In general, the distribution capital costs increase by 33-58% from 2020 to 2050, due to the lower heat density achieved by building renovation, depending on the renovation ambition and the DH market share. The connection rate has a significant impact on the resulting average costs, increasing the connection rate from 50% to 75% can lower the cost by up to 46%. Higher resulting market shares can be reached with accepting higher distribution capital costs that show a linear increase. Assuming the current average distribution capital costs

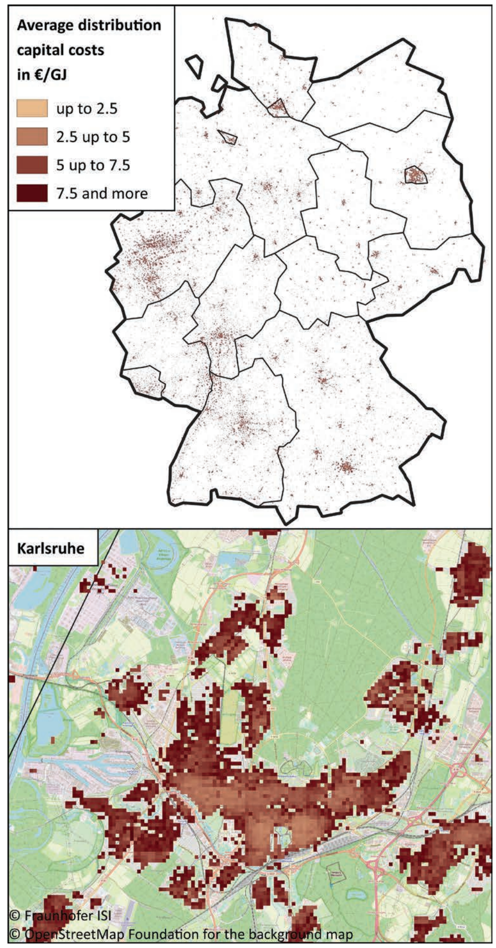

Figure 7: Distribution capital costs in 2050 for DH areas with a connection rate of 75% and a DH market share of 40%, for the *high-refurb* scenario.

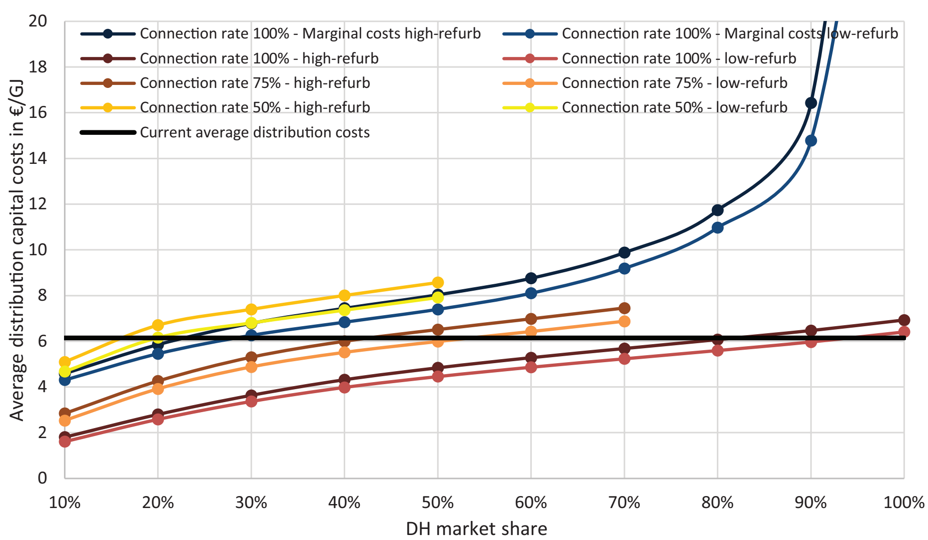

Figure 8: Average distribution capital costs for the connection rates of 100%, 75% and 50% and marginal distribution capital costs for the connection rate of 100% in 2050.

as economic in the future, market shares can be derived from the intersection of the curves and lie between 17% and 43% for the *high-refurb* scenario, and between 22% and 52% for the *low-refurb* scenario in 2050, for connection rates between 50% and 75%, respectively. Compared to today's market share and connection rates, this means a possible increase in the DH share by the factor of 2 – 5.

3.4 Discussion

The results from the empirical analysis with German data highlight that the existence of DH areas correlates with high heat densities and low distribution costs. However, not all regions with high heat densities have been connected to DH, as not in all cities DH systems have been built in the past. The separate analysis of the correlation in West and East Germany shows that the accepted costs probably depend on the political and social situation. A significant share of regions with low heat densities is connected to DH, suggesting that suburban regions could also be connected economically to DH. Furthermore, the broad range of the normal distribution shows that there are more parameters that influence the existence of DH systems.

The average accepted distribution capital costs of the status quo can be used as a threshold for cost-effective distribution costs, i.e., competitive to individual heating solutions. Assuming this threshold is valid also in the future, large DH potentials can be derived. However, building thermal renovation and thus lower heat densities decreases the economic advantage of DH. The densification of existing grids (i.e. increasing the connection rate by connecting more buildings within existing DH supply areas) is a main parameter and could significantly decrease the specific distribution capital costs and offset rising costs due to building renovation. In general, the cost threshold is quite close to possible future costs depending on the different parameters, so a wide range of DH market shares could be economical in the future.

The results of this paper are in line with the literature, finding that heat density is an important factor for DH installation and building renovation could lead to higher distribution capital costs [2, 10, 11, 13, 15]. Comparing the capital costs to Persson et al, 2021 [11], we observe a similar slope of the cost curves with expectably lower costs of up to 50%, as we do not consider the service pipe infrastructure in the costs. The dependency on the connection rate is comparable to Fallahnejad et al., 2024 [15], who derive possible DH market shares in 2050 of 43% and 29% for average connection rates of 100% and 75%, respectively, for a high-renovation scenario with a demand reduction of 60%. The range of 17% and 52% DH market share is slightly higher than the range of previous studies of Germany (13% to 37%) [3], due to the empirical threshold with a higher accepted cost value and the consideration of several parameters.

The empirical analysis of this paper could be conducted for other EU countries, if the Census data is made available on the hectare-level resolution for all member states. The Census 2021 is planned to be published for all EU member states on a raster with the grid size of 1 km² [39], which could serve as a first approach to an EU-wide empirical analysis.

3.4.1 Limitations

It is essential to acknowledge various limitations that have shaped the scope and implications of our study. First, estimating the costs associated with the reinforcement and densification of the DH infrastructure is prone to the uncertainty whether pipe diameters need to be changed. These adaptations are dependent on factors such as increasing connection rates, building renovation efforts and temperature reduction, and were not considered in detail.

Second, the analysis of distribution capital costs neglects components such as supply and transport costs e.g., from heat sources to the distribution grid, losses in the system, and maintenance expenditures. Also, the age structure of existing grids and reinvestment cycles are not available. In the future, the phase-out of fossil fuels will change the heat sources for both DH and individual heating as well as the introduction of 4th and 5th generation DH systems [34] introduce dynamic elements that could alter the configurations and cost dynamics of heating. This will possibly lead to smaller DH networks that were filtered in our dataset. All of these factors will change the threshold of acceptable and economic distribution capital costs, thus limiting the results regarding the economic value and limit the accuracy of our conclusions.

Third, our analysis predominantly focused on heat density as a key factor for current DH deployment. However, future research should analyse additional influential factors, such as local stakeholders' involvement, the availability of heat sources, or the presence of an existing gas grid, as all of these factors could significantly impact DH deployment.

In general, the results on the hectare-level are based on statistical approaches and use several assumptions to fill data gaps, most importantly regarding the renovation status. Thus, they do not necessarily reflect the situation on this high level of spatial allocation and cannot replace regional analyses, e.g. local heat planning.

3.4.2 Further research

The transferability of the empirical correlation to other countries should be analysed, e.g. with the Census 2021 data once they have been published. The balance between renovation efforts and heating decarbonization has so far been studied mostly in case studies and needs to be analysed on the country-level. Mandel et al., 2023 [40, 41] have conducted a thorough economic analysis for a city district, revealing intriguingly close cost economics for renovation, decentralized heating and district heating, showing the necessity of a detailed analysis and including generation costs as well as considering the multiple benefits of energy efficiency. For that, heat generation, transportation and operation and maintenance costs should be included to gain a more comprehensive understanding of the economic competition of DH. Additionally, the cost competition with decentralized heat pumps in buildings as well as 4^{th} and 5^{th} generation DH after the phase-out of decentralized fossil fuels should be analysed. Understanding these changes is crucial for analysing the future economic viability and potential of DH in the evolving energy landscape.

4. Conclusion

This paper assesses the current status of DH in Germany on the local level, derives empirical correlations and identifies future DH demand potentials from these results. By combining insights from various data sources, we conducted a comprehensive empirical analysis of accepted distribution costs of DH in Germany at a hectare-level resolution. We coupled a building stock model with a spatial analysis, taking into account the empirical results and various parameters (different connection rates and building thermal renovation ambition) for a scenario-based assessment of future DH potentials.

Our findings show that while current district heating systems in Germany are primarily concentrated in areas with high heat densities and consequently low distribution capital costs, this parameter alone does not capture all factors influencing DH viability. Only 70% of regions with a suitable high heat density currently have DH. This indicates that other factors also play an important role. These could include the historic implementation of a natural gas grid hindering DH deployment, or the availability of heat resources like coal power plants and the role of active local stakeholders supporting the implementation of DH.

The existence of DH systems is normally distributed over the distribution capital costs, having accepted costs on average of 6.14 €/GJ. This is lower than the assumed range of marginal costs in other studies of 10 to 20 €/GJ, but plausible as marginal costs are about twice the average costs [3]. The empirical threshold value could also be used for other countries, as the existing literature assumes comparable threshold values for EU countries. Using the correlation and the empirical threshold for future scenarios, we can show that DH market shares ranging from 17% to 52% are possible in Germany in the future, compared to 9.2% today. The large range reflects the uncertainty regarding the share of buildings that will be connected within a DH area and the ambition of building renovation efforts. The range of a possible DH market share confirms the existing literature with high market shares of up to 40%. The share of buildings that are connected within a DH area is the most important parameter to decrease distribution costs and thus increase the possible DH market share in the future. Reaching 100% DH connection rates in all DH areas in Germany is not realistic and should be considered as an upper theoretical limit. However, in some areas in Germany currently 90% of buildings are connected in certain areas, showing that high connection rates are indeed realistic and could be reached by local heat supply policies. With lower renovation activity, DH has a greater market potential. An integrated local energy planning should focus on renovating buildings that are not feasible for DH and consider the multiple benefits of energy efficiency. With higher renovation activity, the DH potentials are 17-23% lower compared to lower renovation.

As both decentral heat pumps and large scale heat pumps in DH rely on renewable electricity for heat generation, the effects on the power system need to be considered as well. DH could offer more system integration potentials as large heat storages are in the system that could be loaded in times of low electricity prices. An integrated perceptive is therefore needed in energy planning, e.g. as proposed by the energy efficiency first principle [42] and the smart energy concept [43].

The current revised German heat legislation (Building Energy Act - German: „Gebäudeenergiegesetz", and the Heat Planning Act - German: „Wärmeplanungsgesetz") as well as the EU legislation (Art. 25 and 26 of the revised EED (Energy Efficiency Directive) (EU) 2023/1791, revised in September 2023) are aiming to reach a climate-neutral heat supply in 2045 and 2050, respectively. In particular, the Heat Planning Act as well as Article 25, EED introduce mandatory communal heat planning. Municipalities need to take action to implement or densify DH grids in areas with high heat densities and increase the connection rate by involving stakeholders and the public. Our study shows that local action and policy support for high connections rates are decisive for low costs, leading to a high cost-effective DH share.

DH can be a competitive source of heating in densely populated areas, possibly replacing the gas grid or individual heating systems. Our study underscores the vast potential of district heating as the DH share could be increased by the factor of 2 to 5 compared to today. Energy system studies with a high modelling resolution can support finding a cost-optimal DH share and can integrate the empirical threshold found by the census analysis. A future comprehensive evaluation of cost competition, as required in the EED and suggested by Hummel et al, 2023 [44] on the EU-level and Mandel et al., 2023 [40] on the district level is needed. The emergence of individual heat pumps and technical progress in 4th and 5th generation DH systems pose intriguing challenges as well as opportunities for the future. Ongoing research will be vital in understanding and navigating the heating transition, particularly in terms of competition and integration of these evolving technologies within the context of DH in Germany and the EU.

Acknowledgements

The authors express their sincere gratitude to Lukas Greif for his valuable contribution to this research, especially in developing the structure of the regional model DisCo and the data preparation in his Master's thesis "Modelling of district heating potentials in Germany".

A significant part of this paper was primarily presented at the 9th International Conference on Smart Energy Systems (SES) taking place in Copenhagen on the 12th – 13th of September 2023.

Appendix 1: Detailed description of input datasets

TableAnnex 1: Overview of input datasets used for empirical analysis.

Dataset	Census-Data	Hotmaps - Floor area	Hotmaps - Population density	KfW subsidy report
Type	Number of dwellings per heating installation	Floor area and share per age category (gfa_nonres_curr_density, gfa_res_curr_density, ghs_built_1975_100_share, ghs_built_1990_100_share, ghs_built_2000_100_share, ghs_built_2014_100_share)	Population density (pop_tot_curr_density)	Money paid as subsidies for renovation and energy-efficient buildings
Indicators used	Heating type: District heating and total	Floor area before 1975, 1975-1990, 1991-2000, 2011-2014	Population density	Subsidies for renovation measure of buildings
Spatial resolution	100x100m	100x100m	100x100m	NUTS 3
Definition	Permanent construction with at least one dwelling and one access, which are occupied	Heated gross floor area	Population	Funding in € Mio for: energy efficient building, restructuring, individual measures, supplements, subsidies
Number of data	2,737,253 hectare cells	4,436,097 hectare cells	4,436,097 hectare cells	5 different categories for 401 regions
Publication	2017	2019	2019	2016-2021
Year of data	Written survey of homeowners: 2010 - 2011	Statistical approach: 2012	Statistical approach: 2012	2015-2020
Data protection	Raster cells with one data point are classified as 0, with two data points as 3.	-	-	-

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