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Analysing district heating potential with linear heat density. A case study from Hamburg.

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Abstract

District heating (DH) can play a key role for a sustainable urban energy supply, especially in the presence of a building stock with high heat demands and several decades of useful life ahead. The economic viability of DH depends, among other things, on the distances between heat generators and customers and hence is not automatically given for each urban context.
Many decision support tools for energy planning are currently being developed, which, though differing in complexity, always contain some kind of heat atlas, or heat cadastre – a thematic map representing spatially disaggregated heat demand. We propose extending this approach, combining built environment and urban space layout so that heat demands can be connected to heat infrastructure. Specifically, we analyse the linear heat density (the annual heat demand per metre of grid length) in order to inform strategic heat planning. We use a heat demand atlas, the street layout of the city of Hamburg and an algorithm based on graph theory to group buildings according to their closest street segment and then generate hypothetical heating grid layouts, which connect all buildings within a group. These hypothetical grids represent potential small heating grids or likely modules of a grid. We then transfer the heat demand information from the heat demand atlas to these hypothetical heating grids. That way, we create a dataset containing aggregated groups of buildings, their heat demand and a plausible assumption as to the grid layout and length required to connect them. We then use this dataset in a case study of Hamburg, Germany to (i) identify where potential expansions of existing and construction of new DH grids could take place, (ii) estimate effects of increasing the connection density within urban areas currently supplied by DH and (iii) simulate grid expansions while preserving the current average linear heat density.

Keywords: Heat Density, Graph Theory, District Heating Expansion Potential

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1. Introduction

District heating is recognized as a key technology for sustainable heat supply [1], even in areas with low energy buildings [2]. As district heating has a strong spatial element (due to the heat losses occurring in heat transport), it is no surprise that recent years have seen the emergence of GIS based tools for heat energy planning. Many municipalities develop a heat demand atlas (or heat “cadastre”) of their jurisdictions. These atlases are often based on urban energy demand models (UBEMs) [3], which in their simplest form are building stock models with energy-relevant data. In the following, we illustrate an expansion of the currently dominating approach such that the potential for district heating grids can be mapped and visualized.

2. Methodology

In this paper we use a UBEM, prepared as part of the GEWISS Project Hamburg [4]. It is based on the digital cadastre of the city of Hamburg (ALKIS), the building typology of the German Institute for Housing and Environment (IWU) for residential buildings [5] and the German VDI 3807 guideline [6] for non-residential buildings. Similar to many other building energy models [3,7] we use the ‘archetype’ approach, making use of building ‘archetypes’ which are allocated to cadastral objects. The ‘archetypes’ are typical buildings with energetic properties, usually derived from building samples. Buildings in the ALKIS are represented with a footprint geometry and attributes stored in a database. By allocating archetypes to cadastral objects, an estimation is made of the energetic characteristics of the cadastral objects. The quality of the estimation depends upon how well a building corresponds to its allocated ‘archetype’. The allocation of the ‘archetypes’ to cadastral objects is based upon characteristics of the buildings found in the cadastre that do not include energetic properties but are considered as proxies (obviously, if energetic properties were available for the cadastral objects, the archetypes would be unnecessary).

2.1. Modelling Residential buildings

We use the archetypes of the IWU for the residential buildings. The typology classifies the buildings into a matrix of 5 construction types, 12 construction epochs and 3 retrofit levels (baseline, standard 2014 energy retrofit and passive-house retrofit). For construction epoch, we use the building age found in the digital cadastre. To assign a construction type, we use the floor count and a building type classification found in the ALKIS. Estimating the level of retrofit is a bit of a challenge. We use available information on construction permits and building energy certificates to arrive at a plausible estimation. From our field studies for the GEWISS project we learnt that energy certification of individual buildings which are part of a housing cooperative (which make up large parts of the Hamburg building stock) is in many cases a signal that neighbouring buildings owned by the same cooperative are also retrofitted. Since ownership data is not available we use the plot structure to estimate where such cases could occur. Plots containing a building with an energy certificate are treated as ‘retrofitted’ and all buildings within the same plot receive the same status. Our second source of information on retrofit level – construction permits – is also available only at the plot level. This method is prone to errors, but it constitutes our best guess. Moreover, the exact type and depth of the retrofit is not known and we estimate a dichotomous – ‘yes’ or ‘no’. Given that the energy certificates are from the period 2002-2016 and the construction permits from 2014-2017, the retrofitted buildings most probably vary in their retrofitting. This, however, we cannot mirror with the defined retrofit levels of the IWU typology. We also consider it as too fine modelling for the purpose of our heat demand atlas and the amount of uncertainty associated with the archetype approach in general. With the allocation of the IWU archetypes and a dichotomous retrofit level a specific heat demand value in kWh/(m^2*a) is assigned to each residential building in the cadastre. This value we then multiply with the residential floor area, which is the heat demand reference area for these buildings. The residential floor area we consider being equal to 80% of the gross floor area of any building. Mixed-use buildings we treat as half residential and half non-residential.

2.2. Modelling Non-residential buildings

Estimating the energetic properties of the non-residential building stock poses more of a challenge. Not only is there a lack of data on building retrofits, but building age itself is available for only a small portion of these buildings. The latter is perhaps less of a problem, since age correlates less with heat demand in the non-residential building sector as it does in the residential sector. Non-residential buildings are more heterogeneous in use, geometry and materials and hence are not as easily classified into 'archetypes'. Due to a lack of important information we adopt a simplified approach and use specific heat consumption values from the German VDI 3807 guideline. These values are medians from samples of real measurements. They are grouped in 'archetypes' based only on building use, e.g. administrative buildings, schools, office buildings etc. and two refurbishment levels ("baseline" and "renovated"). The reference area for non-residential buildings in the typology we use (from the VDI 3807 guideline) is the gross floor area which we derive from the digital cadastre using floor count and footprint area without the need for further calculations.

2.3. Heat Demand Atlas Validation

We perform a two-step validation of the heat demand atlas. Since total heat demand is highly dependent on the size of a building, we first validate the estimation of the reference floor area. For the residential buildings, an external validation is possible using data from the 2011 census at the *Stadtteil*[1] level [8]. This data includes total residential floor area for each *Stadtteil*. We sum up the areas of the individual buildings from the heat demand atlas at the same geographic level (*Stadtteil*) and correlate the result with the census data (Fig.1. (a)). The fit of the regression line is very good with a high coefficient of determination (r^2=0.99). The equation with an intercept of zero shows that our model yields an estimated floor area that exceeds the census data by 5%. This is to be expected, given that our heat demand atlas is based on cadastral data from 2018, while the census data is from 2011 and the city of Hamburg has a vibrant real estate market with a lot of new construction every year (for German standards). Externally validating the non-residential floor area is not possible in this way, because the census gathers data only on the residential buildings. Using gross floor area as the reference area for the non-residential buildings reduces the risk of errors with these buildings. An issue exists however, which we still consider problematic – a building with multiple structures or bodies but a single mutual footprint (e.g. a shopping centre with two residential towers). With these buildings, the gross floor area, as we calculate it, would equal the footprint area times the number of floors, which will be an overestimation in many cases. Although this applies to only a small fraction of the building stock, it has very large impacts on some buildings, with total floor areas being off by a factor of 2 or 3. Surprisingly, using 3D data does not solve this problem. The 3D model of Hamburg (available freely online) in both Level of Detail 1 and 2 uses the footprint geometry of the ALKIS as basis and the issue gets propagated. While we are exploring ways to solve this issue, we neglect it for the purpose of this paper, as the effects are mostly local and isolated.

The second validation (Fig.1. (b)) of the heat demand atlas we perform at the city level, where we compare the estimated heat demand to monitored consumption values averaged over the years 2014, 2015 and 2016 [9–11]. It is well known that heat demand (estimates based primarily on transmission losses through the building shell) can greatly differ from real consumption. Therefore, caution has to be observed when comparing the two. In our case, however, the heat demand atlas uses consumption-corrected values for the residential buildings and consumption-based values for the non-residential buildings; hence, the heat demand atlas is comparable with the energy consumption statistics. We adjusted each year's consumption to the long-term average for the Hamburg climate zone using a tool by the IWU based on degree-days from the German Meteorological Service [12] and averaged the result over the three years. We arrive at 17.3 TWh energy consumption for heating and domestic hot water for the entire building stock, excluding heat needed for industrial processes. The estimated heat demand from the heat demand atlas is 19.8 TWh (13% higher). For the residential buildings, this includes useful energy plus system losses without conversion losses so that it resembles the demand a building requires at its substation/heat transfer station.

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[1] An administrative division, roughly equivalent to a neighbourhood. Our case study city of Hamburg is comprised of a circa 100 such *Stadtteile*.

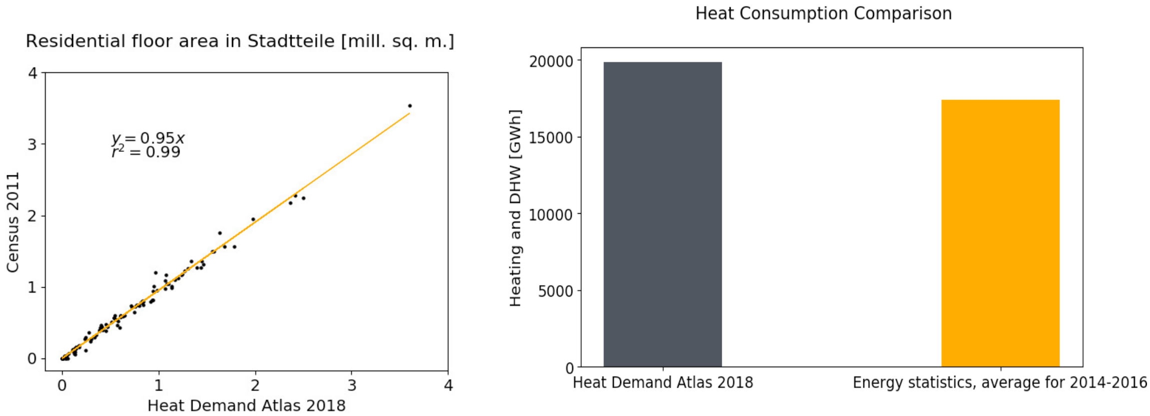

Fig. 1. (a) Correlation of residential floor area between estimations of our heat demand atlas and census 2011 at the *Stadtteil* level; (b) Heat Demand Atlas total heat demand compared to consumption values

The consumption-based specific heat demand of the non-residential buildings as given in the VDI 3807 includes also conversion losses. Note that the energy statistics for Hamburg do not differentiate between heat demand for space heating and domestic hot water (DHW) and so we had to use the estimated national split of end-energy into use categories [13] to estimate the amount of energy consumption only for heating and hot water. Generally, the heat demand atlas performs well. Both floor areas and total consumption come close to values provided in external sources. We decided not to adjust the heat demand totals with the 13% overestimate out of reasons of transparency of the numbers. The overestimation leads to slightly higher heat density, which we account for by considering more conservative cut-off values for it. Of course, total consumption at the city level averages out many of the discrepancies at lower levels. Since we could not validate the heat demand at various levels of aggregation, we consider the atlas good at city and district scales and assume a moderate performance at smaller neighbourhood or urban block scales. For individual buildings, the heat demand atlas can show large discrepancies, not only due to user behaviour problems but also due to the renovation level.

2.4. Linear heat density

Heat density (or Areal Heat Density) in the context of heat planning is usually defined as energy demand per hectare or square meter of urban space. It is used in many heat demand atlases, e.g. the Pan European Thermal Atlas (Peta) or the Saarland heat cadaster [14,15]. We propose using an alternative measure – linear heat density. Linear heat density of a heating grid is defined as the ratio between heat demand (or delivered heat if an existing grid) and heating grid length (supply and return pipes counted as one, also “trench length”). It can come in different units, we use MWh per meter and year - MWh/(m*a). Both types of density are used as indicators for the economic viability of a heating grid. The higher the density, the more heat can be delivered and sold over a unit of the grid, reducing losses and investment costs. Both density types give an important orientation as to a grid’s viability [16,17], although by far not the only decision parameter for the construction of a heating grid. Nevertheless, linear heat density has the advantage (over Areal Heat Density) that non-relevant urban spaces do not enter the measure. The usual problem with the Areal Heat Density (as in yearly energy per hectare of urban space) is the definition of the urban space, when it is actually used as a proxy for the needed grid length. Since the linear heat density directly uses grid length, we consider it as the superior measure of the two. Arriving at a measure for linear heat density requires, however, calculating the grid length. For existing grids, this is straightforward, but since our goal is to estimate potential for heating grid expansion, we need an estimation of the length of a potential new heating grid in areas without one. This we call *hypothetical grid modelling*.

2.5. Hypothetical Heating Grid Modelling

We use the term "hypothetical grid modelling" to refer to the generation of a 2D polyline geometry that connects a number of buildings to each other. An example can be found in [18]. The focus lies on estimating a plausible length and routing of pipelines. Apart from the need for geometry, linear heat density requires a defined building stock for a heating grid. In order to allow a more fine-grained spatial analysis that can be useful also at a local level, we divide the building stock into building groups and generate hypothetical grids for each group (see [19] for the importance of spatial resolution in energy system modelling). These building groups we consider as the buildings served by small heating grids or as groups of buildings served by a larger grid. By mapping the linear heat density for groups we can better analyse the areas which have potential for heating grids. The building groups are based on the plot structure and street layout of the city. The plot structure we consider, since it mirrors property-rights and it is likely that buildings within a single plot would be part of the same heating grid or heat supply solution. Since urban infrastructure and heat supply pipelines in particular usually traverse public spaces or streets we consider the street layout as a good starting point for estimating pipeline routes. We use the street centerlines from a 2D street model [20] and we group the building stock of Hamburg first into buildings with mutual plots and then mutual street segments. A street segment is a part of a street between two junctions.

After defining the building groups, we generate a 2D polyline geometry that connects the buildings in the group to each other, resembling a heating grid. There are a number of different heating grid layouts – radial, circular or multi-circular [21]. The radial grid layout has a main supply pipeline and individual substations/heat transfer stations connect to it. The circular grid layout is similar, but the main pipeline is in the form of a ring. With the multi-circular layout, the main pipeline has multiple rings. For the purposes of the hypothetical grid modelling, we use the radial grid layout, since the building groups are rather small and a ring layout is rarely used at this scale. Furthermore the groups we consider also as grid segments, therefore multiple radial layouts of building groups can be connected and thus form a ring layout. We model the grid layouts with each street segment being the radial, main pipeline. Of course, this is a form of simplification, but one that plausibly represents heating grid layouts. Next, we model the connections from the main pipeline (represented by the geometry of the street segment) to the buildings. We convert each building to a point. Most buildings in the ALKIS have a geographic location associated with their addresses, which in most cases represent the location of the entrance to the building. For the buildings that have this geographic location of the address point i, we use it to represent the possible geographic location of a substation/heat transfer station. For all others we use the centroid point of the geometry. We also project i onto a 2-meter buffer around the building and obtain a point j directly in front of the entrance to each building. This point j we use so that connecting pipes coming from the main pipeline do not (or at least more rarely) enter the buildings at all possible angles. The point j we connect to i (Fig. 2). We then use j to locate the nearest point along the street segment s. However, simply connecting each j to s fails in many locations where it would make more sense to connect a couple of buildings to each other first and then connect the group to the main pipeline. In order to have an algorithm that can decide this based on the concrete spatial constellation, we use an approach from graph theory – a minimum spanning tree (MST) [22]. An MST is a graph that connects each node from a set of nodes n that has a minimal length compared to all other graphs that span n. We use all the points j, s and the vertices of the street segment v as the set of nodes n and create an MST connecting all of them in an optimal (minimal length) way.

The geometry we create by converting the edges of the MST to polylines in 2D space. Since, in reality, optimal solutions are rarely possible, we reweight the distances between nodes so that the algorithm considers some practical aspects.

Firstly, in order to ensure that the main pipeline, represented by all the points s and v is always a continuous pipeline we decrease the distance between each of these points. Secondly, we increase the distances between buildings in different plots with a factor of 2. Note the horizontal distances between the nodes j for each building. In a non-weighted distance matrix each separate connection j to s would mean a non-minimal tree, since the optimal way would be to connect each point j to another point j on the same side of the street and then only one of them to the street segment. However, due to the weighting of the distances the algorithm considers the distance of j to another j as "longer" due to the factor of 2 stemming from the two being in different plots. This means the algorithm prefers connecting a building to the main pipeline or to a building within the same plot. This is in line with the general logic that cascaded connections of multiple buildings are somewhat problematic when it comes to obtaining passage rights for the infrastructure from plot owners. Of course, buildings within the same plot, assumed as having one owner, are not subject to this problem. Generally, these rules can be applied without the use of a MST.

However, since the urban fabric is rather heterogeneous, having strict rules leads to illogical constellations of pipeline routes in some places. For this reason, we use the MST algorithm. It provides flexibility and introduces a tendency towards some rules, but retains the ability to break them if the spatial constellation demands it. In practical terms, the weighting allows the algorithm to connect a building (a) to another one (b) from a different plot, rather than the main pipeline, if a is more than twice as far away from the main pipeline as from b. These rules are a simplification of reality, but we consider them plausible when it comes to pipeline lengths and routes.

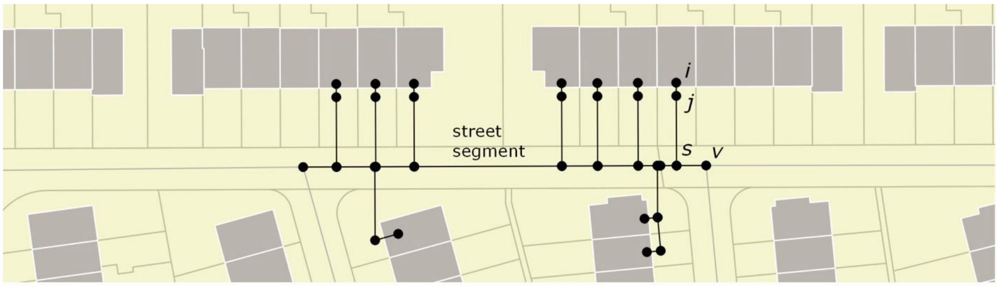

Fig. 2. Nodes of a hypothetical heating grid.

2.6. Hypothetical grids validation

We now compare the lengths of the generated hypothetical grids with lengths of existing grids of different sizes. In this way we estimate the plausibility of the algorithm. We use a vector polyline geometry of the existing main district heating grid of Hamburg, provided by the BUE. Hamburg has a large district heating grid and multiple smaller ones, we use the large one for a city-scale comparison and two smaller ones for a local scale comparison. We spatially intersect the buildings with the pipelines and obtain a subset of the building stock that is connected to each grid. We then use this subset of buildings as the input into our algorithm and generate hypothetical grids for it. We then compare the sum of the length of the hypothetical grids to the actual length of the existing grid. Note that the existing large grid has long main supply pipelines in the western part of the city that connect the coal-fired cogeneration-plant "Wedel" to the city centre. Since our algorithm is designed to estimate linear heat density it cannot directly tackle such specifics as the location of large power plants. Therefore, for the comparison, we manually take out some grid segments from the existing grids and compare only the areas that include a supplied building stock. The total length of the existing grid without these segments is 754 km (773 km with them). The generated hypothetical grids for the same building stock have a total length of 775 km, which is 3% higher than the 754 km of the existing grid (Table 1). This is probably due to the hypothetical grids using street segments, some parts of which are unnecessary and lead to rings within the grid. Having inner rings in the grid layout is observable for existing grids, but to a lesser extent compared to the hypothetical ones. Nevertheless, we consider this a good approximation that allows the use of the algorithm for city-scale analysis of densities and lengths.

Next, we test the performance at a local scale. For this, we compare the lengths of two existing small heating grids to the sum of hypothetical grids for the two respective building stocks (Fig. 3 and Table 1.). The first of the smaller grids is in an area of mainly single-family houses, while the second is in an area with large apartment blocks. In this way, we attempt to validate the results also in different urban settings. Although the grid lengths are close to the existing ones, there are discrepancies when it comes to the layouts of the hypothetical grids. In the area with single-family houses, the pipeline routes of the hypothetical grids are closer to the routes of the existing grids. We expected this, since the algorithm is heavily depending upon the street layout and it is logical that it performs better in areas where the existing grids also follow this pattern. Nevertheless, in the second area, the grids also have overall plausible layouts. Note that the hypothetical grids do not connect all buildings in the two examples. This is the case, since the algorithm divides the building stock into smaller sets of buildings and aims at connecting only them. We defined the algorithm in this way so that it divides the building stock into sub-stocks for which densities can be estimated, rather than create a single grid for a whole input building stock. The latter would mean that densities are averaged out between the different areas of a city, which doesn't allow the analysis of different areas within a city. Overall we consider the algorithm to be useful for estimating linear heat densities. It is not however suited for the planning of a particular grid with exact routing and pipe dimensioning or similar more "concrete" planning tasks.

Table 1. Comparison of total grid lengths of existing grids and the corresponding hypothetical grids.

Type of grid used for validation	Length (Existing) [km]	Length (Hypothetical) [km]	Deviation in %
Main district heating grid	754.0	775.0	+3%
Small grid with single-family houses	16.4	14.4	-13.3%
Medium sized grid with multifamily buildings	21.0	20.4	-3%

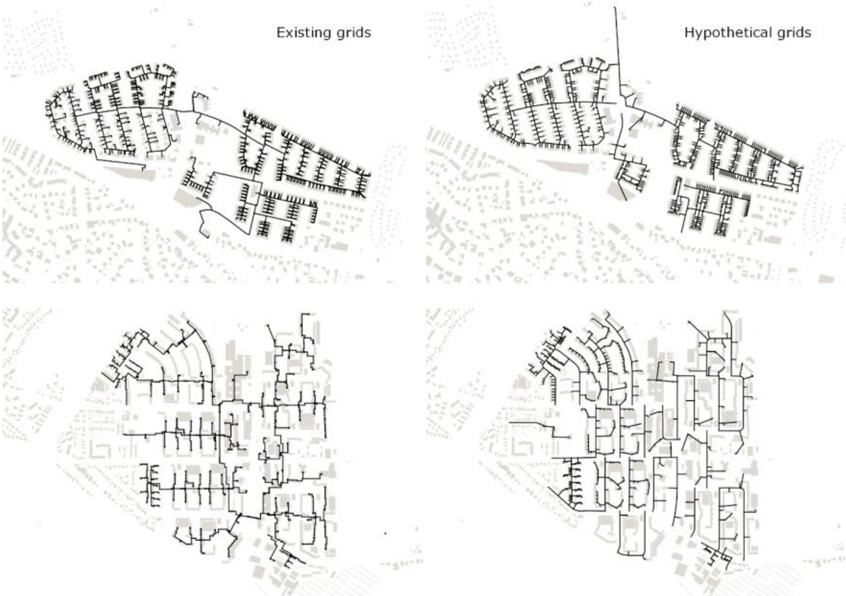

Fig. 3. Existing and hypothetical heating grids.

3. Case study Hamburg

After validating the proposed algorithm, in this section, we apply it to the city of Hamburg in order to show how it can be used for exploring different planning issues. Running the hypothetical heating grids algorithm for the entire building stock of Hamburg together with the street layout resulted in 18 000 building groups and a hypothetical grid for each of these groups. Generally, a value of 1.5 MWh/(m*a) as a cut-off for grid viability is considered a rule of thumb [19,23]. This is an orientation value. It means grids with lower density are less viable since potential investment costs and grid losses become too great in relation to the delivered heat. We adopt a more conservative approach and consider a cut-off value of 2.5. Not surprisingly the central parts of the city showed the highest grid density, but there were numerous other areas with high density and therefore potential for district heating, even given our conservatively chosen cut-off.

3.1. Grid expansion and new grids

Hypothetical grid modelling is especially useful in conjunction with other data to address different planning questions. In this section we overlay the higher density hypothetical grids (>2.5 MWh/(m*a)) with the existing grids

(Fig. 4 left) and urban areas planned for new residential construction [24] (Fig. 4 right). The first map allows the localization of areas, close to the existing grids with high linear heat density, which constitute areas for potential expansion (e.g. the orange ovals in the figure). The second map brings also another aspect into play – finding areas, where new developments can be used as triggers for new grids that combine new and existing buildings.

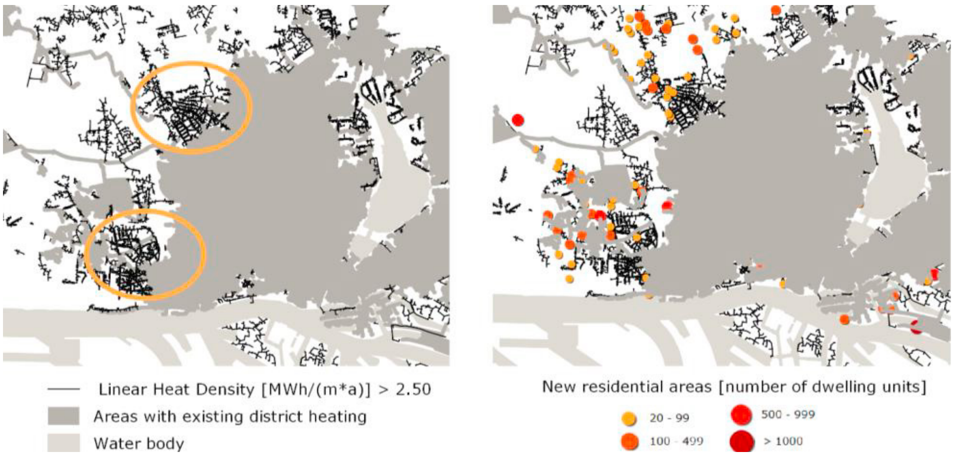

Fig. 4. Hamburg city centre. Analysing potential areas for grid expansion in combination with planned new residential areas.

3.2. Connection density within currently supplied areas

Another application of the hypothetical heating grids is analysing possible unused potential within areas with existing grids. There are many buildings in Hamburg that use other forms of heat supply, although in an area with an existing heating grid. In this case the hypothetical heating grids can be used to analyse the impact of connecting **all** buildings within already supplied areas. Currently the total length of all heating grids is 1 200 km with 4.4 TWh average early heat consumption [11] (corrected with degree days and averaged over the period 2014-2016). This leads to a linear density of 3.7 MWh/(m*a). We defined all buildings within a 40m buffer around the existing grids as "buildings within areas with existing district heating". We then ran the hypothetical grids with this subset of buildings as inputs. The results show a total grid length of 1800 km (+50%), a total heat demand (consumption-corrected) of 7.5 TWh (+59%) and an average density of 4.2 MWh/(m*a) (+12%). This means that there is considerable potential within these areas – currently around 22% of the demand is covered by district heating (4.4 TWh from the estimated 19.8 TWh of the atlas), while this could potentially be 7.5 TWh or 38% and it would also lead to a higher average density. Note that the hypothetical heating grids tend to overestimate lengths at this scale and one could possibly connect these buildings with less new pipeline length.

3.3. Grid expansion simulation

Lastly, we use a simple simulation algorithm to locate grid expansions using the hypothetical grids. We take as input the areas with existing heating grids as polygons (using the 40m buffer to convert the polylines into polygons). We then rank all the hypothetical grids outside these areas according to their distance to an existing grid area. We iterate over the hypothetical grids and if a hypothetical grid has a linear heat density over the current city average of 3.8 MWh/(m*a) we connect the hypothetical to the existing grid using a straight line. Note that the linear heat density of each hypothetical grid is updated with the segment needed to connect it to the closest existing grid **before** the comparison with the city average. We then update the existing grids so that the hypothetical grid from the previous step is counted as "existing". We proceed with this expansion logic for all hypothetical grids. The results are presented in Fig. 5. The simulated expansions amount to 484 km and a total yearly heat demand of 3174 GWh/a (72% of the current district heating consumption) with a density of 6.5 MWh/(m*a), which is significantly higher than the current average. These numbers suggest high potential outside currently supplied areas. Spatially, the expansions are dispersed in different areas of the city. This simulation uses a simplified logic and the entire simulated expansion is most likely not plausible. Nevertheless, this simulation provides an overview of where potentials in urban space lie and is a way of generating ideas about possible future developments.

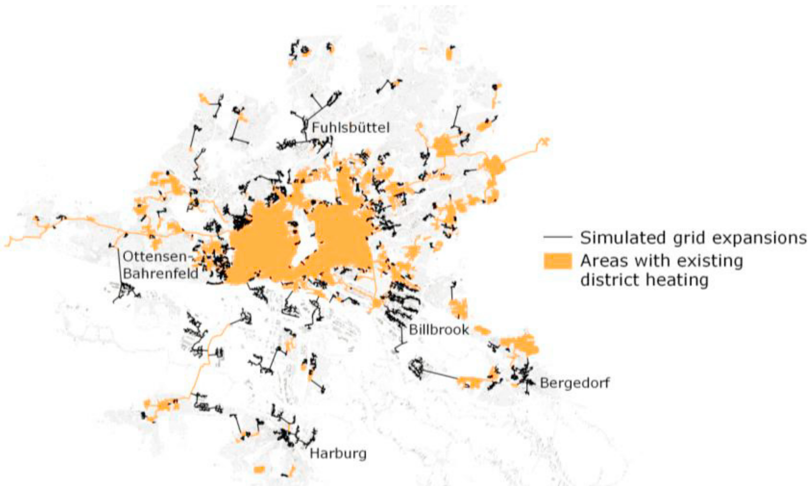

Fig. 5. Grid expansion simulation

4. Conclusion

The goal of the method presented here is to estimate linear heat density in urban space. The linear heat density we consider as a signal for economic viability. Mapping and presenting it can be a way of motivating, giving ideas to or simply bringing together relevant public and private actors. This can support efforts for sustainable heat supply, in this case, the use of district heating. The hypothetical grid modelling we presented is a conceptually straightforward and easily implemented way for estimating linear heat density. Using only a heat demand atlas and the street network as inputs, we managed to map the linear heat density of the entire city of Hamburg. Both the heat demand atlas and the estimated grid lengths we validated against real-world data, which showed a good fit. Of course, the application of this hypothetical linear heat density has its limitations. Important aspects concerning the construction of district heating grids are omitted – e.g. situation of the underground and costs connected with different types of construction. Furthermore, we do not analyse actual economic viability but use the ratio of heat demand and grid length (linear heat density) as a proxy for it. This has the disadvantage that external economic factors (e.g. energy prices) are not considered. On the other hand, district heating grids are a long-term infrastructure that has to be planned with certain economic robustness. Since linear heat density is relatively fixed and not as volatile as energy prices, we consider it plausible to use it as a proxy. Additionally, expected heat deliveries over the coming decades could be a more important parameter than current energy prices, as they also implicate resource efficiency independent of prices. Also, for the decision and potential to construct heating grids, there are other aspects than economics. Institutional issues such as existing heat delivery contracts and plot easements can stand in the way of heating grid expansions. Therefore, it is important to use this method for its specific purpose – mapping and presenting linear heat density as a way of communicating potentials in urban space and providing orientation of economic viability of district heating grids.

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References

[1] Agora Energiewende. *Heat Transition 2030: Key technologies for reaching the intermediate and long-term climate targets in the building sector*. Available at: https://www.agora-energiewende.de/fileadmin/Projekte/2016/Sektoruebergreifende_EW/Heat-Transition-2030_Summary-WEB.pdf; 2017 [accessed 17.04.2018].

[2] Sandvall AF, Ahlgren EO, Ekvall T. Cost-efficiency of urban heating strategies – Modelling scale effects of low-energy building heat supply. *Energy Strategy Reviews* 2017;18:212–23, doi:10.1016/j.esr.2017.10.003.

[3] Reinhart CF, Cerezo CD. Urban building energy modeling – A review of a nascent field. *Building and Environment* 2016;97:196–202, doi:10.1016/j.buildenv.2015.12.001.

[4] GEWISS Project. *GEWISS Geographisches Wärmeinformations- und Simulationssystem [Geographical Heat Information and Simulation System]*. Available at: http://gewiss.haw-hamburg.de/; 2018.

[5] Loga T, Stein B, Diefenbach N, Born R. *Deutsche Wohngebäudetypologie [German residential building typology]: Beispielhafte Maßnahmen zur Verbesserung der Energieeffizienz von typischen Wohngebäuden*; 2015.

[6] The Association of German Engineers. Characteristic consumption values for buildings: Characteristic heating-energy, electrical-energy and water consumption values;91.140.10, 91.140.50, 91.140.60. Berlin: Beuth Verlag; 2018. Available at: http://www.vdi.eu/nc/guidelines/vdi_3807_blatt_2-verbrauchskennwerte_fuer_gebaeude_verbrauchskennwerte_fuer_heizenergie_strom_und_wasser [accessed 16.05.2018].

[7] Li W, Zhou Y, Cetin K, Eom J, Wang Y, Chen G, Zhang X. Modelling urban building energy use: A review of modelling approaches and procedures. *Energy* 2017;141:2445–57, doi:10.1016/j.energy.2017.11.071.

[8] Statistics Office for Hamburg and Schleswig-Holstein. *Stadtteil Profile 2015*. Available at: https://www.statistik-nord.de/fileadmin/Dokumente/Datenbanken_und_Karten/Stadtteilprofile/Stadtteilprofile-Berichtsjahre-2007-2015.xlsx; 2015 [accessed 16.05.2018].

[9] Statistics Office for Hamburg and Schleswig-Holstein. *Energiebilanz und CO2-Bilanzen für Hamburg 2014 [Energy and CO2 balance for Hamburg 2014]*. Available at: https://www.statistik-nord.de/fileadmin/Dokumente/Sonderver%C3%B6ffentlichungen/Energie-_und_CO2-Bilanz_Hamburg/EB_CO2_HH_2014.pdf; 2016 [accessed 17.07.2018].

[10] Statistics Office for Hamburg and Schleswig-Holstein. *Energiebilanz und CO2-Bilanzen für Hamburg 2015 [Energy balance and CO2 balance for Hamburg 2015]*. Available at: https://www.statistik-nord.de/fileadmin/Dokumente/Sonderver%C3%B6ffentlichungen/Energie-_und_CO2-Bilanz_Hamburg/EB_CO2_HH_2015.pdf; 2017 [accessed 17.07.2018].

[11] Statistics Office for Hamburg and Schleswig-Holstein. *Energiebilanz und CO2-Bilanzen für Hamburg 2016 [Energy balance and CO2 balance for Hamburg 2016]*. Available at: https://www.statistik-nord.de/fileadmin/Dokumente/Sonderver%C3%B6ffentlichungen/Energie-_und_CO2-Bilanz_Hamburg/EB_CO2_HH_2016.pdf; 2018 [accessed 17.07.2018].

[12] Institut Wohnen und Umwelt. *Gradtagszahlen Deutschland [Degree days in Germany]: Klimadaten auf Basis von Deutscher Wetterdienst, Offenbach - www.dwd.de*. Available at: http://t3.iwu.de/fileadmin/user_upload/dateien/energie/werkzeuge/Gradtagszahlen_Deutschland.xls; 2018 [accessed 30.05.2018].

[13] Arbeitsgemeinschaft Energiebilanzen e.V. *Anwendungsbilanzen für die Endenergiesektoren in Deutschland in den Jahren 2013 bis 2016 [Final energy consumption by sector and type of use in Germany in the period 2013 2016]*. Available at: https://ag-energiebilanzen.de/#ageb_-_zusammenfassender_bericht_fu____r_die_endenergiesektoren_2013_-_2016; 2017 [accessed 17.07.2018].

[14] Heat Roadmap Europe 4 Project. *Pan-European Thermal Atlas 4.2*. funded by the Horizon 2020 Programme of the European Union. Available at: http://heatroadmap.eu/peta4.php; 2017 [accessed 17.07.2018].

[15] Institut für ZukunftsEnergieSysteme. *Wärmekataster Saarland [Heat Demand Cadastre Saarland]*. Available at: http://geoportal.saarland.de/mapbender/frames/index_ext.php?gui_id=Template_GDZ&WMC=3761#; 2017 [accessed 17.07.2018].

[16] Andreas Pfnür, Bernadetta Winiewska, Bettina Mailach, Bert Oschatz. *Dezentrale vs. zentrale Wärmeversorgung im deutschen Wärmemarkt[Decentralized vs centralized heat supply in the German heating market]: Vergleichende Studie aus energetischer und ökonomischer Sicht*. Arbeitspapiere zur immobilienwirtschaftlichen Forschung und Praxis. Darmstadt: Technische Universität Darmstadt, Forschungscenter Betriebliche Immobilienwirtschaft; 2016.

[17] Jalil-Vega F, Hawkes AD. Spatially resolved model for studying decarbonisation pathways for heat supply and infrastructure trade-offs. *Applied Energy* 2018;210:1051–72, doi:10.1016/j.apenergy.2017.05.091.

[18] Dochev I. *Significance of the accuracy of building heat demand estimations for the planning of heating grids*. Hamburg; 2017.

[19] Jalil-Vega F, Hawkes AD. The effect of spatial resolution on outcomes from energy systems modelling of heat decarbonisation. *Energy* 2018;155:339–50, doi:10.1016/j.energy.2018.04.160.

[20] Hamburg Ministry for Economic Affairs, Transport and Innovation. *Strasseninformationsdatenbank Hamburg [Hamburg Street-Information-Database]*. Available at: http://daten-hamburg.de/transport_verkehr/strassen_und_wegenetz/Strassen_und_Wegenetz_HH_2017-02-28.zip; 2017 [accessed 22.05.2018].

[21] Dötsch C, Taschenberger J, Schönberg I. *Leitfaden Nahwärme [Guidelines for small-scale district heating]*. Stuttgart: Fraunhofer-IRB-Verl; 1998.

[22] Kruskal JB. On the shortest spanning subtree of a graph and the traveling salesman problem. *Proceedings of the American Mathematical Society* 1956:48–50, doi:10.1090/S0002-9939-1956-0078686-7.

[23] Nast M, Harald D, Hartmann H, Kelm T, Kilburg S, Mangold D, Winter H. *Evaluierung von Einzelmaßnahmen zur Nutzung erneuerbarer Energien im Wärmemarkt (Marktanreizprogramm) im Zeitraum Januar 2007-2008 [Evaluation of single measures for the use of renewable energy sources in the heating market]*. Available at: http://www.dlr.de/tt/Portaldata/41/Resources/dokumente/institut/system/publications/MAP-Endbericht_2007-2008_(ohne_Anhang).pdf; 2009 [accessed 22.05.2018].

[24] Hamburg Ministry for Urban Development and Housing. *Wohnungsbauflächenpotenziale [Planned Residential Building Areas]*. Available at: http://metaver.de/trefferanzeige?docuuid=8223B7BD-D194-4230-B436-1607D3BF3BC5; 2017 [accessed 22.05.2018].