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Impact of distribution and transmission investment costs of district heating systems on district heating potential

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Abstract

In this paper, we use a heat density map (HDM) and a plot ratio map to propose a GIS-based method for determining potential DH areas with specific focus on district heating (DH) grid costs. The DH areas are determined via performing sensitivity analyses on the HDM under consideration of predefined upper bound of the average distribution costs. The approach additionally allows for estimation of length and diameter of transmission lines and their associated costs. The outputs are GIS layers that illustrate areas that are economically viable for construction of DH as well as the cost-minimal transmission lines connecting these regions to each other. The impacts of key input parameters like grid costs ceiling and market share on potential and on expansion and extension of the DH systems were studied for the case study of Vienna. The results showed that the increase of DH market share in DH areas under a certain grid cost ceiling significantly reduce average grid costs. In addition, it was revealed that the expansion of DH system without increasing the market share in the DH areas does not effectively increase the share of DH from the total heat demand and leads to higher average grid costs. These results call for policy interventions like spatial heat planning, zoning and implementation of district heating priority areas.

Keywords: District heating potential; Grid investment costs; Heat density map; Plot ratio

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1. Introduction

The investments in district heating (DH) infrastructures help to integrate diverse renewable and low-carbon energy sources and reduce the dependency on a single energy source. Especially with the 4th generation of DH system, due to its low working temperature, it is possible to supply heat, either directly or indirectly, with a wide range of energy sources such as geothermal, solar, wind, biomass, excess heat etc. [1]. However, the initial investment in the DH grid is usually associated with uncertainty regarding future heat sales and the potentially achievable connection rate of DH. In this paper, the DH grid investments are studied from various perspectives such as grid cost ceiling, investment periods, DH market share and expected levels of the energy saving in future due to building retrofitting and renovation. In addition, the impact of these parameters on DH potential and connection of remote areas to the DH grid is studied as well.

Nomenclature

A	Set of all coherent areas
AF	Annuity factor
C	Set of pipeline dimension steps
$C_{1,T}$, $C_{2,T}$	Construction costs constant [€/m] and Construction costs coefficient [€/m^2]
Cap_{ij}	Required capacity in the pipeline connecting area *i* to *j* [MW]
c_{dist}, c_{trans}, c_{grid},	Average specific costs of distribution grid, transmission grid and both of them [€/MWh]
c_grid_max	Specific grid cost ceiling [€/MWh]
c_dist_max	Specific distribution grid cost ceiling [€/MWh]
d_a	Pipe diameter [m]
D_t	Annual heat demand in year "*t*"
e	Plot ratio
FLH	Full load hours
G	Coherent area with highest DH heat demand
Inv_T	Investment in year "*T*"
L	Total trench length [m]
l_{ij}	Border-to-border distance of area *i* and area *j*
m	Investment period [years]
MS_0, MS_m	DH market share at the beginning (year "0") and the end (year "*m*") of the investment period
n	Depreciation time
PowStep	Capacity of a pipeline for a give dimension
q_i	Boolean variable determining if the coherent area *i* is part of DH system or not
Q_t	Heat demand supplied by DH in year "*t*"
r	Interest rate
S	Ratio of accumulated energy savings
$SPCTL_{ij}$	Specific cost of transmission line connecting area *i* to area *j*
TLC_{ij}	Annualized specific cost of transmission line connecting area *i* to area *j*
TLB_{ij}	Boolean variable showing if transmission line from area *i* to *j* should be built
w	Effective width of distribution pipeline [1/m]
y_{ij}	Boolean variable determining if there is a line from coherent area *i* to coherent area *j*

The connection of buildings to the DH grid via long pipes not only is expensive, but also increases the heat losses. Therefore, the linear heat density (transferred heat per length of pipeline) is considered as a key elements in the assessment of DH distribution grid costs [2–4]. The linear heat density was traditionally quantified based on empirical data. Another method is to estimate the pipeline length based on street routes and subsequently, calculate the linear heat density. This method was used in [5–8]. This is done by determining shortest street pathway required to connect all buildings in an area. The method uses computer algorithms and can be easily implemented. However, it requires detailed georeferenced data and long processing time for larger areas like a city. The method may also ignore waterways, highways, or physical barriers if they exist in the study area. Furthermore, a 100% connection rate of buildings to the DH system, even if realized in the future, usually does not occur at once in practice – an important issue that should be considered in investment decisions. In addition, the implementation of method for lower connection rates is also difficult to implement and may lead to inaccurate results. Persson and Werner proposed an analytical approach for estimating the linear heat density using the concept of effective width [9]. They addressed the limitations caused by lack of empirical data for tuning the results. Later on, they used the method for estimating the distribution cost of district heating based on heat demand and plot ratio and demonstrated the competitiveness of DH in inner city areas for several European cities [10]. Since then, the approach has been applied widely in different study areas [11–15]. The advantage of this method is its easy implementation and application for large regions as well as the higher calculation speed.

The determination of potential DH areas can be used for either construction of new DH systems or extension of them. In that sense, the GIS methods provide a good insight to study areas and have been used frequently by researchers and energy planners [3,12,16–18]. The GIS methods used for estimation of DH potential can be divided into 3 main categories. In the first category, the heat sources and sinks are indicated with a very local focus in order to precisely determine the expansion and extension potentials. In this way, the major heat consumers such as shops, hospitals, hotels, offices etc. are determined and the DH potential calculated. For example, Finney et al. determined the existing and emerging heat sources and sinks and subsequently, depending to their vicinity to the existing DH infrastructure, calculated the potential for expansion of DH system via separate network as well as for the extension of the existing networks [19]. In the second category, a heat demand threshold is used for the determination of areas with DH potential [16]. In other words, it is assumed that the DH supply of all dense areas with a heating demand of above a certain level is economically viable. This method can be additionally used to determine the suitable technology for heat supply depending on the heat density, as done in [17]. The third category, calculates the distribution costs using the concept of effective width, as proposed by Persson and Werner [10], and compares them with other heat supply options. For instance, Nielsen and Möller divided the grid investment into distribution grid and transmission grid investment [4]. For the distribution costs, they used the analytical approach based on the concept of effective width. For the transmission lines, on the other hand, they calculated the costs based on required capacity and shortest path between the center of a potential DH area and center of the closest existing DH system to that area. Finally, areas that had the total cost of lower than individual supply options, were considered as potential DH expansion areas.

The strength and weakness found in above enumerated methods are explained in the following. Having a detailed local focus and determining heat sources and sinks with the intention of providing a reliable, accurate result for a given case study, is highly beneficial for making concrete investment decisions (category 1). However, this process requires a very detailed information about the suppliers and consumers and replicating it in other regions requires almost the same amount of effort. The introduction of the heat density threshold for determination potential DH areas, as was done in category 2, is much easier to apply to larger areas and requires less processing time. However, sometimes the obtained regions are close to each other and interconnection of these regions may economically justify the supply of heat to their surrounding areas with DH as well. In other words, it may underestimate the existing potential. Furthermore, the small zones are prone to demand reduction, which can risk the investment for connecting them to the DH grid. In comparison to the category 2, category 3 provides a brighter picture from pre-feasibility study of implementing DH systems. However, it should be noted that implementation of DH system in new areas is a time consuming procedure and the uncertainties regarding heat saving actions and the expected future market share should be included in the study. Additionally, it should be noted that having common transmission line corridor between several potential areas, instead of building multiple parallel lines, could improve the feasibility of connecting more potential areas to the DH system. This leads to a better estimation of required pipeline diameter and as a result, reduction of costs of heat losses in transmission lines.

Consequently, this paper proposes a method for determining DH potential with respect to investment periods, expected future market share of DH system, expected level of energy savings. Additionally, the cost-optimum transmission lines and their capacities for connecting the coherent areas are determined. The method is applied to the case study of Vienna and the obtained results are illustrated in GIS-layers.

2. Approach

For the economic assessment of investment in DH system, both marginal heat generation costs and heating grid investments must be studied [2]. However, to simplify the problem and focus on grid investments, we introduce a parameter as grid cost ceiling (c_grid_max). This parameter implies that the marginal heat generation costs have been studied separately and to keep the DH system competitive, the grid costs may not exceed this cost ceiling. Additionally, the DH grid costs (c_{grid}) is split up into distribution grid capital costs (c_{dist}) and transmission grid capital costs (c_{trans}). This is shown in Eq. (1).

$$c_{grid} = c_{dist} + c_{trans} \quad [€/MWh] \quad S.t.: \; c_{grid} \leq c\_grid\_max \;\; ; \;\; c_{dist} \leq c\_dist\_max \tag{1}$$

The main input data for this study are a heat density map (HDM) and a plot ratio map. These data are obtained from the preliminary version of European HDM and plot ratio map provided by Hotmaps project [20]. Both the HDM and plot ratio map have a resolution of 100x100m. Each cell of these maps is referred as a pixel in this work.

2.1. Distribution costs

One of important means to reach the EU targets for reduction of greenhouse gases is improving the efficiency and decreasing energy use in buildings [21]. In term of heat consumption, this lead to implementing measures for energy-efficient thermal envelope retrofit of existing buildings and constructing new buildings with higher thermal insulation levels. These measurements have direct impact on heat demand and influence investments in DH systems. Considering an investment period of "*m*" consecutive years on DH grid, the annual heat demand in t^{th} year of investment (D_t) is calculated using the heat density map from the first year of investment and the ratio of accumulated energy saving (S) at the last year of investment (Eq. (2)).

$$D_t = D_0 \cdot \sqrt[m]{(1-S)^t} \qquad 0 \leq S \leq 1 \;\; ; \;\; t \in \{0,1,2,...,m\} \tag{2}$$

The reduction of heat consumption in European buildings in the future, can potentially affect the capital costs and consequently, the market share of DH. Therefore, the current market share as well as the targeted market share at the end of investment period should be included in the investment calculation. In this paper, the term "market share" is referred to "market share within DH areas" unless it is clearly stated. Accordingly, the expected heat demand that should be supplied by DH in each year (Q_t) and in each pixel is calculated based on the DH market share at the beginning of the investment period (MS_0) and the expected market share at the last year of investment (MS_m):

$$Q_t = D_t \cdot \left[MS_0 + t \cdot \frac{MS_m - MS_0}{m} \right] \tag{3}$$

The distribution grid investment required in each pixel of the HDM is calculated using the proposed method by Persson & Werner [10] with additional considerations regarding the investment period. The study area is categorized in three groups (inner city areas, outer city areas and park areas) based on the plot ratio value. Subsequently, the linear heat density (L) is calculated using the concept of effective width (w) in Eq. (4). Afterwards, the average pipe diameters in distribution grid is estimated Eq. (5). Finally, the distribution grid investment in year T is calculated by Eq. (6).

$$L = 1/w = 1/\left(61.8 \cdot e^{-0.15}\right) \tag{4}$$

$$d_a = 0.0486 \cdot \ln\left(Q_t / L\right) + 0.0007 \tag{5}$$

$$Inv_T = \frac{C_{1,T} + C_{2,T} \cdot d_a}{\left(\sum_{t=0}^{m} \frac{Q_{T+t}}{(1+r)^t} + \sum_{t=m+1}^{n} \frac{Q_{T+m}}{(1+r)^t} \right) / L} \tag{6}$$

The parameters used in Eq. (4-6) are as follows: Q_t is part of annual heat demand (D_t) that is supplied by DH in year t [GJ/a], C_1 is the construction cost constant [€/m], C_2 is the construction cost coefficient [€/m^2], d_a is the average pipe diameter [m], L is the total trench length [m]. C_1 and C_2 are set according to the plot ratio, r is interest rate and n is depreciation time.

As it is shown in Eq. (3), it is possible that the market share at the end of investment period (MS_m) decreases or remains equal to the beginning of the investment period. The DH system should be capable to cover the DH demand (Q_t) at all times of the investment period. Therefore, for the calculation of the investments and potentials, the highest annual DH demand during the investment period (Q_{max}) should be considered. For the calculation of distribution grid capital costs in Eq. (6), the annual DH demand is considered to remain constant after the last year of investment period. This assumption is made in order to focus on the investment period only.

2.2. Determination of coherent areas

Pixels with low heat demand have high distribution costs and therefore, it is not economic to connect them to the DH system. We define a pixel demand threshold of 1GWh/km^2 for removing such pixels. By eliminating these pixels from the map, we obtain groups of pixels that are attached to each other. Each set of these attached pixels constitute small zones that in this paper, are referred as "coherent areas". Afterwards, the distribution costs in each coherent area are calculated and the ones with costs of below the upper bound (*c_dist_max*) are extracted. Subsequently, the pixel threshold is increased with a small step (0.1GWh/km^2) and the previous step is repeated. This process is continued until no pixel above the threshold remains. The result would be a set of coherent areas, all with distribution costs of bellow the defined distribution cost ceiling. Fig. 1 shows the flowchart of these steps.

In practice, determination of coherent areas starts by selecting regions with higher heat densities. Here, this process is done the other way around in order to speed up the calculation process. It should be noted that this has no influence on determination of coherent areas since the distribution cost upper bound is considered in each loop.

2.3. Transmission line model

Transmission lines connect coherent areas to each other and constitute one connected DH grid. The analysis of two or more detached DH systems is not in the scope of this study. The aim of this step is to connect as much coherent areas as possible without exceeding grid cost ceiling (*c_grid_max*). The connected coherent areas that constitute the DH system are referred as "**economic coherent areas**" in this paper. The determination of economic coherent areas as well as the cost-minimal transmission lines and their capacities are determined in an optimization procedure. This is done by introducing a prize-collecting spanning tree problem.

In the first step, the border-to-border distances of coherent areas (l) from each other should be calculated. The coherent areas are labeled from one to N (Eq. (7)). Considering "N" coherent areas, this will give an NxN distance matrix. The transmission pipeline capacities (*PowStep*) and their specific costs are obtained from Table 1. The pipeline specific costs are annualized over the lifetime of the system. The coherent area with highest DH heat demand (G) is considered as the only available heat source. It produces the heat for itself and all other economic coherent areas.

$$A = \{1, 2, ..., N\} \tag{7}$$

The prize-collecting spanning tree problem is defined so that the objective would be to maximize the difference between the revenue from heat sales in economic coherent areas and the costs imposed by construction of transmission lines (Eq. (8)).

$$\max \quad c\_grid\_max * \sum_i Q_{\max,i} * q_i - \sum_i \sum_j TLC_{ij} * l_{ij} * y_{ij} \qquad \forall (i, j) \in A \tag{8}$$

Here, A is the set of all coherent areas; $Q_{max,i}$ is the highest heat demand that is supplied by DH in area i through the investment period; q_i is a Boolean variable determining if the coherent area i is part of DH system or not; TLC is the annualized specific cost of transmission line connecting area i to area j; l_{ij} is the the border-to-border distance of area i and area j; y_{ij} is a Boolean variable determining if there is a line from coherent area i to coherent area j.

The objective function, on the one hand, maximize the supplied heat by DH and on the other hand, finds the cost-optimum combination of the pipelines. The objective function is subject to three groups of constraints: 1) minimum spanning tree (MST) related constraints 2) pipeline capacity related constraints 3) economic constraints. These groups are explained in detail in the followings.

2.3.1. Minimum spanning tree (MST) related constraints

The coherent areas and transmission lines can be considered as a graph. The aim of using MST constraints is to connect all economic coherent areas with minimum number of transmission lines. In order to achieve this goal, the number of transmission lines should be just below the number of economic coherent areas (Eq. (9)). This rule should be true for any subset of the graph and no loop should exist in the final tree (Eq. (10)). Here, it is assumed that between two coherent areas, the heat can only flow in one direction (Eq. (11)). Since the number of economic coherent areas is not clear before the optimization, additional constraints are required as well. There must be one transmission line entering to an economic coherent area (Eq. (12)). On the other hand, a transmission line can be drawn from a coherent area, only if one transmission lines has been entered to it (Eq. (13)). Also, a transmission line can be constructed between two "economic" coherent areas (Eq. (14)). Self-loops should not exist in the graph (Eq. (15)). The Eq. (16) makes sure that the coherent area G is one of the economical areas.

$$\sum_i \sum_j y_{ij} = \sum_i q_i - 1 \qquad \forall (i,j) \in A \tag{9}$$
$$\sum_i \sum_j y_{ij} \le |S| - 1 \qquad \forall S \subseteq A \;;\; \forall (i,j) \in A : i \in S, j \in S \tag{10}$$
$$y_{ij} + y_{ji} \le 1 \qquad \forall (i,j) \in A \tag{11}$$
$$q_i \le \sum_j \sum_i y_{ji} \qquad \forall i \in A - \{G\} \;;\; \forall j \in A \tag{12}$$
$$y_{ij} \le \sum_h \sum_i y_{hi} \qquad \forall i \in A - \{G\} \;;\; \forall (j,h) \in A \tag{13}$$
$$2 * (y_{ij} + y_{ji}) \le q_i + q_j \qquad \forall (i,j) \in A \tag{14}$$
$$y_{ii} = 0 \qquad \forall i \in A \tag{15}$$
$$q_G = 1 \tag{16}$$

2.3.2. Pipeline capacity related constraints

The required capacity in MW in a pipeline (*Cap*) is calculated by dividing the total annual energy demand transferred through that pipeline (in MWh per year) by 3000 full-load hours (*FLH*). The capacities depend on the existence of the pipelines (y_{ij}) and the demand in the economic coherent areas ($Q_{max,i}*q_i$). The capacities of pipelines are bounded so that the solver can converge faster (Eq. (17-22)).

$$Cap_{ij} \ge y_{ij} * Q_{\max,j} / FLH \qquad \forall (i,j) \in A \tag{17}$$
$$Cap_{ij} \le \left(\sum_h Q_{\max,h} - \sum_r \left(y_{ri} * Q_{\max,r}\right)\right) / FLH \qquad \forall (i,j) \in A \;;\; \forall h \in A - \{G,i\} \;;\; \forall r \in A - \{G\} \tag{18}$$
$$Cap_{ij} - y_{ij} * Q_{\max,G} \le 0 \qquad \forall (i,j) \in A \tag{19}$$
$$\sum_j Cap_{ij} - \sum_j Cap_{ji} = q_i * Q_{\max,i} / FLH \qquad \forall i \in A \;;\; \forall j \in A - \{G\} \tag{20}$$
$$\sum_j Cap_{Gj} = \left(\sum_j q_j * Q_{\max,j}\right) / FLH \qquad \forall j \in A - \{G\} \tag{21}$$
$$Cap_{ii} = 0 \qquad \forall i \in A \tag{22}$$

Table 1. Total cost of transmission pipes including projecting, field work, pipe work, materials, and digging, based on [4] with 55°C temperature difference.

Step (C)	Dimension DN	Capacity [MW] (*PowStep*)	Specific Cost [EUR/m] (*SPCTL*)
0	32	0.2	195
1	40	0.3	206
2	50	0.6	220
3	65	1.2	240
4	80	1.9	261
5	100	3.6	288
6	125	6.1	323
7	150	9.8	357
8	200	20	426
9	300	45	564
10	400	75	701
11	500	125	839
12	600	190	976

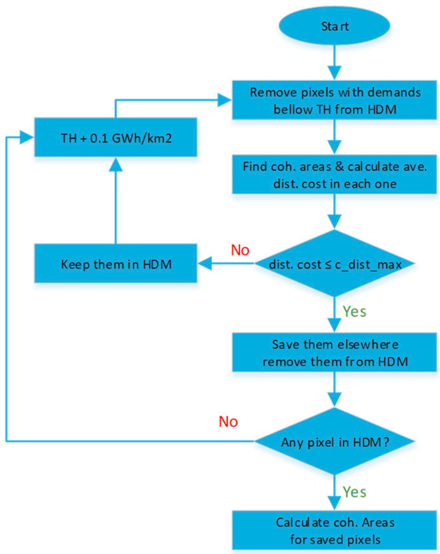

Fig. 1. Flowchart of determination of coherent areas (TH: threshold)

2.3.3. Economic constraints

The distribution grid cost of economic coherent areas are included in total grid costs. Transmission lines costs, on the other hand, are calculated in the optimization model. Based on the required capacity in a pipeline (*Cap*), a suitable step from table 1 should be chosen. Here, the steps are labeled from 1 to 12 (Eq. (23)). Accordingly, the pipe capacity (*PowStep*) and the specific annualized transmission line costs (*TLC*) are calculated. The transmission line Boolean variable (*TLB*) is used to find the right cost and capacity of pipelines (Eq. (24-28)). The grid cost ceiling also should not be exceeded. This condition is fulfilled by Eq. (29).

$$C = \{1, 2, 3, \ldots, 12\} \tag{23}$$
$$TLC_{ij} = AF * \sum_k TLB_{ijk} * \left(SPCTL_k - SPCTL_{k-1}\right) \qquad \forall (i,j) \in A \;;\; \forall k \in C - \{0\} \tag{24}$$

$$TLB_{ijk} \leq y_{ij} \qquad \forall (i,j) \in A \ ; \ \forall k \in C \tag{25}$$
$$TLB_{ij(k+1)} \leq TLB_{ijk} \qquad \forall (i,j) \in A \ ; \ \forall k \in C - \{0, last\_step\} \tag{26}$$
$$0 \leq Cap_{ij} - \sum_k \left(\left(PowStep_k - PowStep_{k-1} \right) * TLB_{ij(k+1)} \right) \qquad \forall (i,j) \in A \ ; \ \forall k \in C - \{0, last\_step\} \tag{27}$$
$$0 \leq \sum_k \left(PowStep_k - PowStep_{k-1} \right) * TLB_{ijk} - Cap_{ij} \qquad \forall (i,j) \in A \ ; \ \forall k \in C - \{0\} \tag{28}$$
$$0 \leq \sum_i \left(q_i * Q_{\max,i} * \left(c\_grid\_max - c_{dist_i} \right) \right) - \sum_i \sum_j \left(TLC_{ij} * l_{ij} \right) \qquad \forall (i,j) \in A \tag{29}$$

3. Parametrization

A key input parameter of the model is the DH grid cost ceiling (*c_grid_max*). For the case study of Vienna, we study the DH grid cost ceilings from 8 EUR/MWh to 17 EUR/MWh. In this study, the ratio of distribution grid cost ceiling (*c_dist_max*) to grid cost ceiling (*c_grid_max*) was set empirically by running sensitivity analyses on this ratio for various regions across Europe. The sensitivity analyses revealed that the factor of 0.95 provides a good balance between inclusion of coherent areas in DH system and connecting remote coherent areas to the DH system (Eq. (30)). As the results from [6] shows, this value may reduce to approximately 0.85 if street routes instead of the Euclidean distances are used for the transmission line corridors.

$$c\_dist\_max = 0.95 \cdot c\_grid\_max \tag{30}$$

In the last years, the share of district heating from the total heat demand in Vienna has been around 30% [22]. This is equivalent to 36% market share within DH areas [23]. The model is run for various expected market share increases over the investment period from 2018 until 2030 ranging from 40% to 90%. Additionally, the total heat demand reduction due to building retrofitting and higher thermal efficiency of newly constructed buildings is considered. This is reflected in the ratio of accumulated energy saving (S) with 5%, 10% and 15% heat demand reduction in 2030 compared to 2018. A discount rate of 5% and depreciation time of 30 years are considered in the calculations. Table 2 shows the summary of the input parameters and scenarios.

4. Results

Here, the outputs are depicted in GIS layers and the impacts of market share and energy savings are presented.

4.1. GIS Layers

Fig. 2a shows the HDM of Vienna at the beginning of the investment period. As it can be seen in the map, the heat density is at highest in the center and decreases as going toward the suburbs. Fig. 2b illustrates the impact of the expected market share at the end of the investment period (MS_m) on the expansion of DH system. It can be seen that the establishment of DH in the suburban areas only at high market shares (>70%) is economically feasible. The expected accumulated energy saving at the end of the investment period (S), however, has a reverse impact on the expansion of the DH (Fig. 2c). In other words, the higher the energy saving measurements, the less suburban areas can be supplied by DH at a certain grid cost threshold.

Finally, Fig. 2d shows some of coherent areas and transmission pipelines from a closer look. Additionally, the required capacity for the transmission pipelines are shown. Based on this capacity, a suitable pipe dimension is selected and accordingly, the pipeline costs are calculated in the model.

4.2. Impact of market share and energy savings

Fig. 3 provides a summary of obtained results from various scenarios. In the figure, the points represent the calculated average grid costs obtained from the model under a certain scenario. The red lines in Fig. 3a and 3b show the current status in Vienna, i.e. the 30% of the total heat demand that is supplied by DH system.

In the Fig. 3a, the focus is on the impact of the market share on the calculated specific grid cost. As it can be seen, under a certain grid cost ceiling (eg. *c_grid_max* = 14 EUR/MWh), as the market share at the end of the investment period (MS_m) increases, the specific grid costs decrease. At the same time, the share of total heat demand supplied by DH system, increases dramatically. The figure also highlights the importance of achieving a high market share. For instance, at the cost of less than 8 EUR/MWh, it is possible to supply more than 60% of total heat demand if the market share of 90% is reached. In the Fig. 3b, the focus is on the impact of the grid cost ceiling on the calculated specific grid costs. As it can be seen, higher grid cost ceilings, do not necessarily lead to the increase of supplied heat with DH. Considering the section 2.2, increase of the grid cost ceiling has a direct impact on areal expansion of the coherent areas. However, areal expansion of DH areas without increasing the market shares, has low impact on the increase of the share of total heat demand supplied by DH. This trend can be seen in Fig. 3b. It can be concluded that, the increase of the market share within a DH area, has a higher impact on increase of the heat supply by DH compared to the expansion of the DH grids to the suburban areas. This has also high impact on the reduction of specific grid costs. These can be realized by policy interventions like spatial heat planning, zoning and implementation of district heating priority areas [24].

Fig. 3c depicts the impact of expected accumulated energy saving on the specific grid costs. It can be concluded from the graph that the increase of the accumulated energy saving, leads to slight increase of the average grid costs and decrease of the share of total heat demand that is supplied with the DH system.

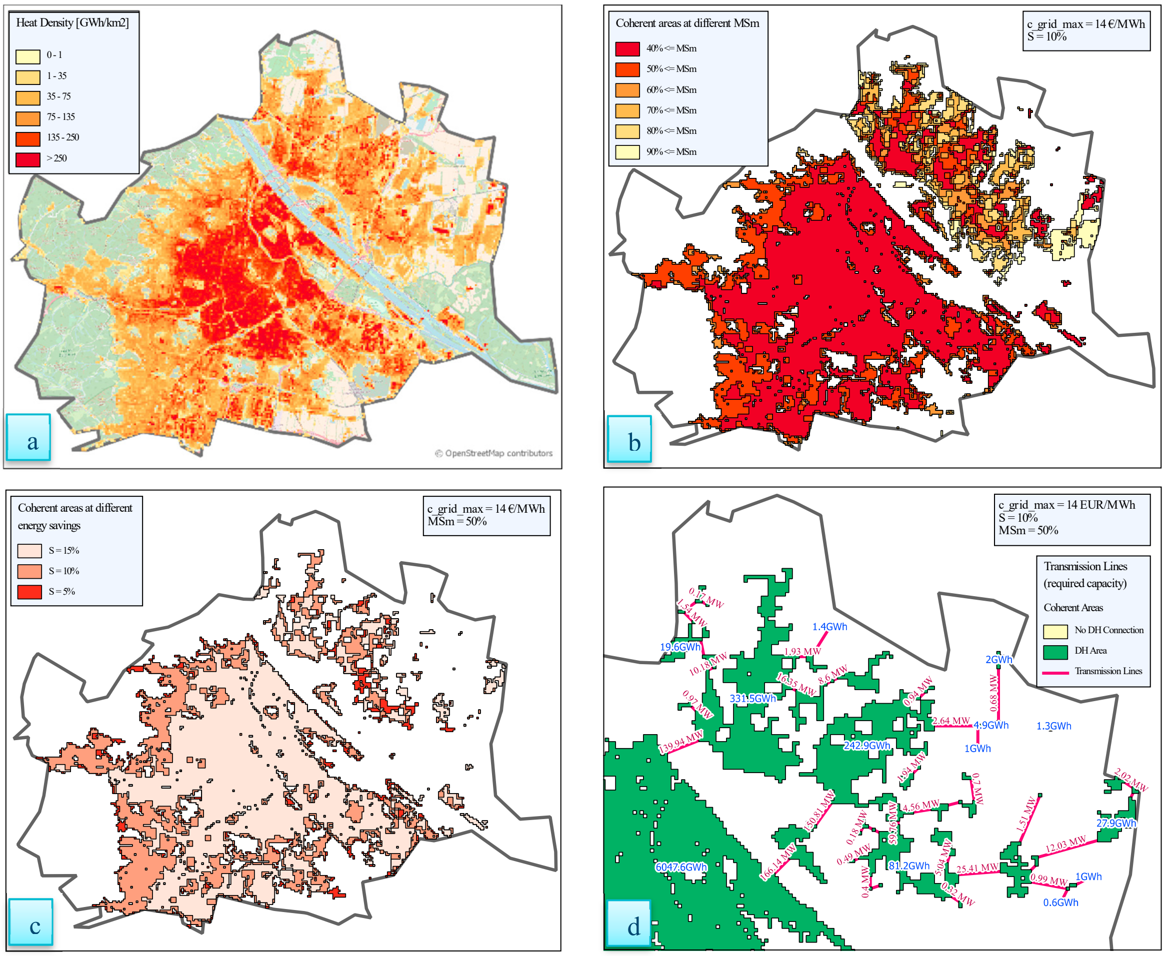

Fig. 2. (a) Heat density map of Vienna; (b) Coherent areas at various expected market share at the end of investment period (MS_m); (c) Coherent areas at various expected accumulated energy saving (S); (d) Optimum pipeline connection and required pipeline capacity

5. Discussion

In order to construct a DH network, the technical aspects such as water flow, heat losses and ground elevation should be simulated and optimized in detail. However, the purpose of this article is not to design the distribution and transmission grids, but rather to develop a method for estimation of the cost-optimal size and cost of the grid on a regional scale and calculate the DH potential. The approach can be applied to any urban and rural area to examine different DH grid investment strategies. The outputs of the approach do not limit to a DH potential value; but also reveal the investment strategy that can lead to higher heat supply with DH system at the same average grid costs. The optimization model not only determines economic coherent areas for connection to the DH grid, but also identifies the cost-minimal transmission line passages and required pipeline sizes. Furthermore, the output GIS layers provide an intuitive illustration and perspective to an investment plan.

Fig. 3. (a) Impact of market share at the end of investment period (MS_m) on obtained average grid costs and on percentage of the total heat demand supplied by DH in last year of investment for different *c_grid_max* levels; (b) Impact of grid cost ceilings (*c_grid_max*) on calculated average grid costs and on percentage of the total heat demand supplied by DH in last year of investment at different market share levels (MS_m); (c) Impact of expected accumulated energy saving (S) on the specific grid costs and on percentage of the total heat demand supplied by DH in last year of investment

6. Conclusion

In this paper, a HDM and a plot ratio map were used for the study of DH potentials. Distribution grid costs in each pixel of the HDM were calculated and the coherent areas with an average distribution grid cost of below the distribution grid cost ceiling were determined. Subsequently, via an optimization model, the economic coherent areas were determined and the optimum corridors for connecting these areas as well as the capacity of transmission pipelines were calculated. The method allows for consideration of DH market share and accumulated energy saving for the calculation of grid costs and DH potentials.

The proposed method was applied to the case study of Vienna and various scenarios were examined. The results showed that the increase of grid cost ceiling leads to expansion of the coherent areas to suburban areas and accordingly, increases of the share of total heat demand supplied by DH. However, this trend slows down as the grid cost ceiling rises. Increase of the market share at coherent areas, on the other hand, leads to reduction of average grid costs and has a high impact on growing the share of supplied heat by DH from total heat demand. In other words, higher DH market share can contribute to boost the competitiveness of DH systems. Finally, the increase of the accumulated energy saving leads to a slight increase of the average grid costs and decrease of the share of total heat demand that is supplied with the DH system. Overall, the results are backing the call for policy interventions like spatial heat planning, zoning and implementation of district heating priority areas.

References

[1] Lund H, Werner S, Wiltshire R, Svendsen S, Thorsen JE, Hvelplund F, et al. 4th Generation District Heating (4GDH). Energy 2014;68:1–11. doi:10.1016/j.energy.2014.02.089.
[2] Reidhav C, Werner S. Profitability of sparse district heating. Appl Energy 2008;85:867–77. doi:10.1016/j.apenergy.2008.01.006.
[3] Andrews DD, Krook-Riekkola A, Tzimas E, Serpa J, Carlsson J, Pardo-Garcia N, et al. Background Report on EU-27 District Heating and Cooling Potentials, Barriers, Best Practice and Measures of Promotion. Luxembourg: Publications Office of the European Union; 2012.
[4] Nielsen S, Möller B. GIS based analysis of future district heating potential in Denmark. Energy 2013;57:458–68. doi:10.1016/j.energy.2013.05.041.
[5] Eikmeier B, Klobasa M, Toro F, Menzler G. Potenzialerhebung von Kraft-Wärme- Kopplung in Nordrhein-Westfalen. Ministerium für Klimaschutz, Umwelt, Landwirtschaft, Natur-und Verbraucherschutz des Landes Nordrhein-Westfalen; 2011.
[6] Nielsen S. A geographic method for high resolution spatial heat planning. Energy 2014;67:351–62. doi:10.1016/j.energy.2013.12.011.
[7] Unternährer J, Moret S, Joost S, Maréchal F. Spatial clustering for district heating integration in urban energy systems: Application to geothermal energy. Appl Energy 2017;190:749–63. doi:10.1016/j.apenergy.2016.12.136.
[8] Nielsen S, Grundahl L. District Heating Expansion Potential with Low-Temperature and End-Use Heat Savings. Energies 2018;11:277. doi:10.3390/en11020277.
[9] Persson U, Werner S. Effective Width: The Relative Demand for District Heating Pipe Lengths in City Areas. 12th Int. Symp. Dist. Heat. Cool. Tallinn Est. Sept. 5th Sept. 7th 2010, Tallinn University of Technology; 2010, p. 128–131.
[10] Persson U, Werner S. Heat distribution and the future competitiveness of district heating. Appl Energy 2011;88:568–76. doi:10.1016/j.apenergy.2010.09.020.
[11] Persson U. District heating in future Europe: Modelling expansion potentials and mapping heat synergy regions. Doctoral thesis. Chalmers University of Technology, 2015.
[12] Müller A, Büchele R, Kranzl L, Totsching G, Mauthner F, Heimrath R, et al. Solarenergie und Wärmenetze: Optionen und Barrieren in einer langfristigen, integrativen Sichtweise (Solargrids). Technische Universität Wien, Institut für Energiesysteme und elektrische Antriebe, Energy Economics Group; 2014.
[13] Möller B, Werner S. STRATEGO D 2.2: Quantifying the Potential for District Heating and Cooling in EU Member States. University of Flensburg; 2016.
[14] Leurent M, Da Costa P, Jasserand F, Rämä M, Persson U. Cost and climate savings through nuclear district heating in a French urban area. Energy Policy 2018;115:616–30. doi:10.1016/j.enpol.2018.01.043.
[15] Leurent M, Da Costa P, Rämä M, Persson U, Jasserand F. Cost-benefit analysis of district heating systems using heat from nuclear plants in seven European countries. Energy 2018;149:454–72. doi:10.1016/j.energy.2018.01.149.
[16] Gils HC, Cofala J, Wagner F, Schöpp W. GIS-based assessment of the district heating potential in the USA. Energy 2013;58:318–29. doi:10.1016/j.energy.2013.06.028.
[17] Connolly D, Lund H, Mathiesen BV, Werner S, Möller B, Persson U, et al. Heat Roadmap Europe: Combining district heating with heat savings to decarbonise the EU energy system. Energy Policy 2014;65:475–89. doi:10.1016/j.enpol.2013.10.035.
[18] Artur Wyrwa, Yi-kuang Chen. Mapping Urban Heat Demand with the Use of GIS-Based Tools. Energies 2017;10:720. doi:10.3390/en10050720.
[19] Finney KN, Sharifi VN, Swithenbank J, Nolan A, White S, Ogden S. Developments to an existing city-wide district energy network – Part I: Identification of potential expansions using heat mapping. Energy Convers Manag 2012;62:165–75. doi:10.1016/j.enconman.2012.03.006.
[20] Pezzutto S. Hotmaps D2.3 WP2 Report – Open Data Set for the EU28. 2018.
[21] Truong NL, Dodoo A, Gustavsson L. Effects of heat and electricity saving measures in district-heated multistory residential buildings. Appl Energy 2014;118:57–67. doi:10.1016/j.apenergy.2013.12.009.
[22] Energiebilanzen. Stat AUSTRIA n.d. https://www.statistik.at/wcm/idc/idcplg?IdcService=GET_PDF_FILE&RevisionSelectionMethod=LatestReleased&dDocName=022717 (accessed May 8, 2018).
[23] Fortschrittsbericht über die Umsetzung des Klimaschutzprogramms (KliP) der Stadt Wien n.d.:252.
[24] Büchele R. Policies for RES-H/C: Results of the quantitative assessment (D4.2) n.d.:159.