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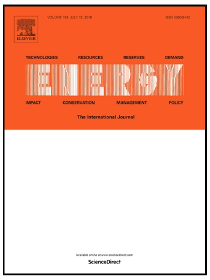

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Heat Roadmap Europe: Identifying Local Heat Demand and Supply Areas with a European Thermal Atlas

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ABSTRACT

In 2016 the first Strategy for Heating and Cooling of the European Union has shown that district heating and cooling networks can integrate renewable energies in an increasingly energy-efficient built environment. At the same time, the heating and cooling sector is probably the most diverse and least mapped component of the European energy system. The aim of the Pan-European Thermal Atlas is to improve the knowledge base for the geographical distribution of heat and cooling demands across Europe. Demand densities of the demanded thermal services themselves, the spatial coherence of these demands, and their location relative to sources of heating greatly affect the economy of district heating schemes compared to individual solutions. The objective is therefore to develop a comprehensive model, which can be used to a) quantify heat demands by density, b) group coherent areas with demands into prospective supply zones, c) produce supply curves for these zones, and d) ultimately calculate local energy mixes on the basis of allocated excess heat as well as renewable energy sources. The developed method spatially disaggregates national demand data to high-resolution geospatial data on urban structures. The resulting atlas allows for an advanced quantitative screening process, which can establish the basis for energy systems analyses relying on geographically explicit information on the heating demand and supply volumes and costs. The present paper presents version 4 of the Pan-European Thermal Atlas, which takes another step towards higher spatial resolution and confidence in comparison to its predecessors, version 1 to 3. For the first time, a 100m resolution heat atlas of Europe is being presented, which may help describing the heating sector in the required spatial resolution. By means of spatial statistical analyses using ordinary least square linear regressions, multiple spatial inputs such as population, degree of built-up and its derivatives are turned into a coherent model of the urban tissue. Plot ratios form the basis of models of heat demand in single and multi-family residential

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buildings as well as the service sector. Prospective district heating areas have been delineated, and the resulting zoning of heat supply has been linked to a resource-economic analysis, which allows for cost-supply studies in disaggregated form. The present heat atlas version 4 is now available for 14 countries that altogether represent 90% of the heat demand in the 28 European Union member states. First results are being presented with emphasis on the achieved methodological improvements. Moreover, a newly developed online mapping system is being presented, which will assist in mapping the new geography of heating and cooling demands and supplies.

KEYWORDS

Heat Roadmap Europe, GIS, district heating, heat supply, heat demand density

1. INTRODUCTION

In its Heating and Cooling Strategy published in February 2016, the European Commission (EC) [1] put attention to the heating and cooling sectors of Europe, which stand for more than 50% of the total final energy demand in Europe [2]. Heating and cooling supply had received little attention until then [3], with few and mostly national or regional policies, plans and strategies but without integrating various sectors such as buildings, transport and industry, which will help to incorporate larger amounts of renewable energy [4]. Also, only a few countries currently have dedicated policies that regulate heat demand and supply. Main emphasis is on improving the building performance, either through deep renovation or the gradual replacement of the building stock with zero-energy buildings [5]. However, strategies to achieve a significant reduction of greenhouse gas emissions, import reliance and costs by means of combined demand and supply sector efficiency measures are largely absent [6]. The consequence is that national heating strategies are substantially weak and the sector, despite its importance, is left without clear targets to utilize its significant potential of energy efficiency investments and the utilization of renewable and excess heat.

Previous studies of the Heat Roadmap Europe (HRE) research initiative have indicated significant synergies between energy efficiency and the development of district heating [2]. Final heat demands could cost-effectively be reduced, while excess heat and renewable energy could see increased utilization [7]. Possible district heat supply shares of 40 – 70% of the heat demands in European Union (EU) member states (MS) were identified [8]. It appears that most of the heat demand could be met with renewable energies and excess heat from industry and power generation at no fuel cost, at significantly reduced greenhouse gas emissions, as well as at reduced energy import reliance and including the potential of higher employment.

The heating sector of Europe is characterised by great diversity in terms of supply technologies, building properties, settlement structures, costs, and regulations. This makes the formulation of identical and uniform national strategies irrelevant. Instead, plans for heat supply need to be based on local information. The nature of heat supply requires a local analysis of heat demand densities and the distribution of heat demands within urban and rural areas. In most countries however, there is a lack of (publically) available data on the distribution of heat demand.

Therefore, the formulation of strategies and policies requires a quantification of the potentials and costs of de-carbonizing the heating sector. Various means to achieve the latter exist, such as enhancement of end-use efficiency in buildings, the use of renewable and excess heat sources, individual heat pumps, or the establishment of collective heat supply infrastructures such as district heating (DH) and the likely use of excess heat potentials, low-enthalpy heat from renewable sources, as well as the sectoral interconnection (power to heat).

In the literature, existing research includes heat atlases, which describe current heat demands and the potentials to develop district heating. Blesl *et al.* [9] describe a heat atlas for Baden-Württemberg in Germany to identify model regions for heat supply. Similarly, Sächsische Energieagentur [10] has prepared an excess heat atlas for Saxony, and Geomer [11] has developed commercial software for a heat atlas for all of Germany. In the UK, national heat atlases [12] as well as atlases for London [13] and Scotland [14] have been produced. Gils *et al.* [15] have prepared a heat atlas specifically for the assessment of district heat potentials in the USA, while Soltero *et al.* [16] have built a decision support system to identify potentials for the co-generation of heat and power (CHP) in Spain. In Denmark, where heat supply planning has a long history, and where the public data infrastructure is highly developed, heat atlases have been prepared since the 1970s; recent examples are Möller *et al.* [17] as well as Petrovic and Karlsson [18]. Most of these heat atlases are being used for district heat expansion planning under consideration of energy efficiency and the use of renewable energy sources. Möller and Lund [19] mapped possible conversion of individual natural gas boilers to district heating supply and modelled the consequences for the Danish energy system using a heat atlas of current and potentially reduced heat demand. Sperling and Möller [20] studied the overall benefits of end-use energy savings and district heating expansion scaled-down to town level. The same heat atlas was used by Zvingilaite and Balyk [21] to model heat savings in buildings with different shares of district heating. The method of mapping was further refined by Nielsen and Möller [5]. Finally, Grundahl *et al.* [22] modelled district heating expansion potentials in Denmark comparing consumer versus socio-economics. Common to these heat atlases and applications is that they are mostly based on locally and regionally available data, with the exemption on Denmark, where national building registers facilitate the development of such. Still, no coherent heat atlases for the entire continent exist at the desired spatial resolution. The present research therefore ultimately aims to extend the body of knowledge with a cross-border heat atlas for all of Europe.

In the HRE research initiative, three earlier studies contributed to the development of a spatially disaggregated Pan-European Thermal Atlas (Peta). While Peta 1 was limited to the description of heat demands and possible supplies on the Nomenclature des Unités territoriales statistiques (NUTS) 3 level [6], Peta 2 already achieved a geographical resolution of 1km^2 [7], at which supplementary analyses at small-scale statistical levels such as NUTS-3 could be carried out [23]. Peta 3, developed as part of the EU Stratego Project, partly was based on a resolution of 100m [8]. However, its limitations lay in the confinement to urban areas alone, its restricted statistical confidence levels [24] and the lack of geographical coverage, see Table 1.

However, geographical coverage is only one aspect of the present research. Most examples of heat atlases do not go beyond mapping, leaving out the necessary technical, economic and planning information to provide the basis for developing heat supply strategies. Hence an atlas may need to calculate heat demand densities for defined area units; map coherent areas where district heating is technically possible; and identify the economic potential of district heating. In other words, such a tool must be geographically explicit and quantitative. To address this knowledge gap, the present paper presents a coherent and consistent heat atlas, based on the experiences from earlier HRE projects.

Table 1 addresses main features and shortcomings in the previous versions of Peta. It can be seen that geographic resolution and coverage have been expanded, while introducing a coherent set of methods to map demands, identify potential district heat supply areas, calculate the costs of district heating networks, and present a web mapping application for dissemination.

The original contribution of the Peta series to science is the bridging of the gap between demand and supply, and the explicit description of possibilities to develop DH in energy units, costs and geographical zoning. Based on the previous work of the HRE research initiative (HRE1-3), the present paper addresses the development of an atlas of heat demands and prospective district heating networks to achieve a representative demarcation of heat supply potentials and costs. The raster-based atlas has a spatial resolution of 100m, equivalent to a grid cell size of 1 hectare.

Table 1: Overview of the main features of previous Peta versions.

Peta version	Main features	Coverage	Main disadvantages
Peta 1 (2012)	Heat demand distributed to NUTS-3 level	EU27	Impossible to know the extent of DH areas.
Peta 2 (2013)	1km population raster to distribute all heat demands. Heat demand density statistics per MS.	EU27	Lack of resolution. Limited focus on DH. Lack of dissemination.
Peta 3 (2015)	Heat demand (residential, service) distributed to 100m grid by means of population, land use and basic regression. Mapping of distribution investment costs, supply areas, renewable energy. MangoMaps web mapping.	Stratego countries CZ, HR, IT, RO and UK	Limited coverage. Rural areas not included.
Peta 4 (2017)	Advanced multilinear regression to model plot ratios. Coherent database to model demands, distribution costs, supply areas, allocation of excess heat, allocation of renewable energy. Advanced web mapping with ArcGIS Online.	HRE countries (14 MS)	Front end and back end largely disconnected.

In order to do so, the HRE4 project quantified the heat required, and the investment costs of supply infrastructures [25]. The potential for savings will be part of the next iteration, when the HRE4 project advances. The contribution to the scientific advancement of the heat strategy sector is the fact that for the first time, coherent heat supply strategies can be formulated for up to 50,000 individual settlements across Europe, as well as for the rural areas outside these settlements. The authors believe that this is a strong decision basis to be explored in the near future.

In chapter 2 the methods are being described. First, a geospatial model for the quantitative mapping of the built environment is documented, which results in sectoral plot ratio maps. These form the basis of a distribution of national heat demands to a 100m resolution, which are then validated against earlier heat atlases. Investment costs of heat distribution networks are being calculated on the basis of heat demand densities. The combination of heat demands and distribution investment costs allows for the generation of cost-supply curves on a national scale, as well as for individual supply areas. A method of delineating these prospective district heat supply areas is being described. The results in chapter 3 show applications and examples of the developed heat atlas. A web-based mapping tool for the dissemination and result presentation is being described in chapter 4 of this paper, before concluding in chapter 5.

2. METHODS

The overall aim of heat planning is to identify how much heat to supply where, by which technology and at which costs. Initially, heat demands need to be quantified by location. Then, the costs of potential DH distribution infrastructure can be modelled. Also, prospective supply areas for collective heat supply technologies will have to be delineated. All three aspects combined by spatial analysis allow for an assessment of potentials and costs by technology, scale of operation, and location. For geographically and economically delineated supply areas, locally available excess heat or renewable energy supplies can eventually be mapped and used to model local district heating energy supply mixes.

2.1. Quantitative mapping of the built environment

Spatially distributed heat demand data or even a coherent database for the location of buildings, their type and floor space is absent for all of the European Union, despite initiatives like the “Infrastructure for Spatial Information in the European Community” (INSPIRE) [26], whose objective is to develop common spatial data infrastructures for policies and activities that affect the environment. In other words, uniform and complete geographical and numerical data on the built environment remains to be incomplete. Even topographical maps of uniform character, applicable for all EU member states, are not available yet, least not in the public domain. Open source maps such as OpenStreetMap (OSM) [27] still deliver an incomplete and occasionally erroneous cartographical representation of building footprints. Above all, apart from statistical sources on national levels, no data exist, which contain concise, local information on physical building properties such as floor area, number of floors, height, age etc. Quite unique is therefore the Danish national register of individual buildings BBR (Bygnings- og boligregisteret) [28], which comprises an address-level geocoded database to describe the physical built environment with high detail and confidence. At this time however, it is far-fetched yet to expect similar data bases for other European countries, which would allow for bottom-up modelling of the heating sector.

Therefore, national heat demands need to be distributed in a top-down manner to statistically modelled floor areas of buildings in the residential and the service sector. The quantification of building space per area unit of one raster cell with an edge length of 100m (equivalent to 1 hectare) has to rely on a geo-statistical approach that uses readily mapped phenomena such as land cover, land use intensity and similar information derived from satellite images to estimate building intensities in a bottom-up manner. These data and their derivatives form the independent variables in a statistical relationship, in which known records of the built environment, such as BBR data, are the dependent variables. The resulting model of floor area densities for residential buildings, differentiating single- und multi-family buildings, and service sector buildings can be used to distribute nationally known and forecasted demands in order to generate high-resolution raster maps of the heating and cooling demands. The advantage of this method is its low cost and fast speed, compared to collecting heat demand data or patch-working national, regional and local datasets. The expected disadvantage is the lower confidence in modelled results. It is being accepted that the quantitative mapping of the built environment presented here never can be a precise account for the location, area and type of existing buildings. Rather, the authors aim at presenting a representative model of the built environment.

Several considerations were made to develop the multilinear regression models. First, it was assumed that the relationship between the already mapped floor space in Denmark and the parameters land cover, percentage of built-up areas, population density and degree of soil sealing is similarly proportional in all of Europe. This is necessary due to the lack of fine-grain building data in most European countries. Second, the quality of these remotely sensed phenomena was considered to be equal across all of Europe. Similarly, this disregards the different confidence in mapping on national scales, particularly for population data. Finally, a linear model is certainly a very rough estimate for the relation between the mapped phenomena and the desired output. Different cultural-historic context, planning practices and socio-economic conditions have all put their footprint on how the built environment is spatially distributed in Europe.

Nevertheless, the explanatory models developed are rooted in basic assumptions of urban architecture and empirical urban mapping as also described by Nel·lo *et al.* [29]. First, a number of hypotheses were made, e.g. that floor area is positively correlated to population or the percentage of built-up land. Second, different building types, e.g. high-rise and low-rise dwellings, may show different neighbourhood patterns of the percentage of built-up land. Accordingly, derivatives of some variables were tested. For example, a relative low average degree of soil sealing in a defined circular neighbourhood may be an indicator of low-rise residential areas, while the high neighbourhood sum of soil sealing will help to identify urban centres, where service sector and high-rise residential buildings may be predominant. Also the length of roads within one hectare, the land use class, or a high-resolution model of gross-domestic product (GDP) layer were chosen as candidates for the regression analysis.

Individual building data of the Danish national building register BBR were summarized to a 100m grid, and Ordinary Least Square (OLS) multilinear regressions were carried out between the recorded floor area and various parameters available from public spatial, predominantly remotely sensed data: The European Environment Agency (EEA) maintains a database for the degree of soil sealing [30] and CORINE (coordination of information on the environment) land cover 2012 [31]; the Joint Research

Centres (JRC) of the European Commission have published a European Settlement Map (ESM) 2016, which describes the share of built-up areas of raster cells [32]; and recently the JRC made available a new population grid [33]. All these data are openly available at a uniform 100m grid following INSPIRE standards and sharing the same spatial reference system. Derivatives of these data, e.g. the neighbourhood mean (NbrMean) or neighbourhood sum (NbrSum) values of the ESM map as proxies of urban centres, were calculated using the ArcGIS Desktop10.2 Spatial Analyst (Advanced license) software. A series of OLS tests were carried out on a trial-and-error basis using ArcGIS Spatial Statistics to examine combinations of these data in order to establish correlations between the different parameters. As an example of this considerable effort, Table 1 shows the significant combinations of parameters and the statistical evaluation of these for multi-family houses.

The table is an overview of the approach of selecting combinations of parameters. It can be seen in the table that each of the parameters $ESM_{\%}$ (percentage of built-up area), ESM^3 (the cube of $ESM_{\%}$), P_{ha} (population per hectare) as well as the sum of the percentage of built-up areas in a radius of 300m around a cell (NbrSumESM%) have different relevance and explanation value for the floor areas. In this case, this confirms the obvious reasoning that multi-storey dwellings are prevalent in populated places, and it shows that the other variables contribute to improving the model.

Table 2: Coefficients for the different parameters of the undertaken regression analyses for the multi-family houses

Intercept	$ESM_{\%}$	$ESM_{\%}{}^3$	P_{ha}	$NbrSum_{ESM\%}$	R^2
-145.8	18.6				0.06
-110.4			26.4		0.3051
-58.2	-3.8		27.7		0.3070
14.1	-11.2	0.003	27.7		0.3118
-68.9	-9.9		26.6	0.1	0.3139
14.1	-11.2	0.003	27.7		0.3119
7.4	**-18.1**	**0.003**	**26.6**	**0.1**	**0.3194**

Several statistical tests to determine significance, autocorrelation etc. were included from the ArcGIS Geostatistical Analyst Extension: Probability and Robust Probability tests indicated that all coefficients tested were statistically significant ($p < 0.01$). High (> 7.5) Variance Inflation Factors (VIF) indicated [34] that some explanatory variables were redundant [35]; these were subsequently excluded from the model. Finally, a Jarque-Bera statistic test [34] was carried out to indicate whether model predictions were biased. This test scored negative, although it can be seen from Figure 1 that the residuals are not normally distributed on a larger scale. Perhaps the sample area for this test needs to be enlarged to include the obvious large scale pattern of residuals, which seem to be correlated to the output variable.

Table 3: Aggregation on 1km² level

	R^2 on hectare level	R^2 of floor area aggregated to 1km²
Single-family houses	0.27	0.73
Multi-family houses	0.32	0.94
Service sector buildings	0.09	0.55

Compared to the estimates made for the single-family houses and especially for service sector buildings, multi-family houses estimations have higher coefficients of determination (R^2), see Table 3probably because of higher homogeneity in the built environment. The generally low coefficients of determination are the results of a very high diversity of urban structures and poor representation in the urban structures mapped by the ESM dataset. If the estimated floor areas are aggregated to a resolution of 1km², see Table 3, then coefficients of determination rise to between 0.55 and 0.94, which is satisfactory to very good. It should be mentioned here that R^2-values depend on context. The large number (about 40,000) of observations from the rasterized BBR increases the confidence in the model results.

It can be seen from the table that multi-family houses are generally better explained by the model compared to single-family houses. This is convenient, since for planning district heating areas the actual location of multi-family houses is more important than the location of single-family houses. Experiences from earlier studies [18] confirm that the heat demand in single-family houses is more uniformly distributed over larger areas but highly diverse in small neighbourhoods.

Although a high coefficient of determination is a good basis for deciding upon a combination of input parameters, it is not the only one. The "look" of the ready map gives important clues for how an urban area should be represented in the model.

Next, using the multilinear regression parameters, the floor area per 1ha cell was calculated for single-family and multi-family residential buildings as well as service sector buildings. Calculations were made for all EU member states. The resulting floor areas were converted to integer values in order to save disk space and no-data and negative values were set to zero. Negative values occur for multi-family floor area in areas with predominately low-rise buildings.

Figure 1 compares, for the area of Copenhagen, Denmark, the actually registered, the calculated and the residual (the difference between known and estimated) areas of the multi-family houses floor area model. The first map depicts the actually registered areas summarized to the 100m grid used in Peta. The map in the middle shows the estimated building areas, while the map in the bottom shows the standard deviation of the residuals. It can be seen that the model generally gives an appropriate picture of the built environment, although it tends to underestimate areas in urban centres, while overestimating areas in semi-urban areas. The uneven distribution of residuals reveals that the present example may need another variable to explain urban areas. This source of error however, is levelled out by distributing heat demand, because not the absolute values matter, but the proportional distribution.

To conclude, the visual and geographical appearance, which is an important aspect in assessing the results beyond calculated coefficients of performance, is deemed to be adequate. The consequence of the rather low coefficients of determination documented above is that while the 100m grid may give a representative example of the likely distribution of building areas in an urban area, it cannot locate the built environment individually within a 1ha resolution. For the calculation of heat demands, the model therefore has to include a proportional distribution between the building types, normalised by population, rather than the absolute area values themselves.

Single-family residential floor area per hectare, see Table 4, was calculated as follows:

$$A_{\mathrm{floor,ha,SFH}} = -6.7 + 30.6 \cdot \mathrm{ESM}_{\%} + 6.8 \cdot \mathrm{NbrMean}_{\mathrm{Soilsealing}} - 0.48 \cdot \mathrm{ESM}_{\%}^{2} \qquad \textbf{Equation 1}$$

for all cells where ESM is not 0 and considering only results larger 0m²/ha, whereby the floor area in non-built-up areas is kept at zero.

Table 4: Parameters and their units and comments for the floor area calculation of single family houses.

$\mathbf{A_{floor,\ ha,SFH}}$	**[m² / ha]**	**floor area of single family houses**
$\mathbf{ESM_{\%}}$	[%]	ESM built-up area coverage of hectare cell
$\mathbf{NbrMean_{Soilsealing}}$	[-]	Neighbour Mean of seal sealing (300m radius)

Similarly, multi-family residential floor area was calculated using this formula:

$$\boldsymbol{A_{floor,ha,MFH} = 7.4 \ - 18.1 \cdot ESM_{\%} + 26.6 \ \cdot P_{ha} + 0.1 \ \cdot \ NbrSum_{ESM} \ + 0.003 \ \cdot ESM_{\%}^{3}}$$

Equation 2

for all cells where ESM is not 0 and considering only results larger 700m²/ha as it is derived from the mapping of building areas from BBR at hectare level that the minimum size of such a building is 700m².

Table 5: Parameters and their units and comments for the floor area calculation of multi-family houses

$\mathbf{A_{floor,\ ha,MFH}}$	**[m² / ha]**	**floor area of multi-family houses per hectare cell**
$\mathbf{ESM_{\%}}$	[%]	ESM built-up area coverage of hectare cell
$\mathbf{NbrSum_{ESM}}$	[-]	Neighbour Sum of ESM built-up (600m radius)
$\boldsymbol{P_{ha}}$	[1/ha]	population per hectare cell

Finally, service sector floor area has been modelled using population, the neighbourhood sums of ESM and soil sealing, as well as GDP and the cube of ESM as variables.

$$A_{floor,ha,ser} =- 1188 - 6.3 \ \cdot P_{ha} - 0.7 \ \cdot NbrSum_{ESM} + 0.7 \ \cdot NbrSum_{Soilsealing} + \quad 0.006 \cdot GD \cdot ESM_{\%}^{3}$$

Equation 3

for all cells where ESM% is larger than 50%; otherwise $floor\ area_{ser}$ = 0; and considering only results larger 0m²/ha. Please observe that population has a negative parameter, and that the intersect is negative at 1,188 m²/ha. This means that service sector buildings only appear at higher values of the variables, suggesting a concentration of service sector buildings as initially hypothesized.

Table 6: Parameters and their units and comments for the floor area calculation of single family houses

$\boldsymbol{A_{floor,ha,ser}}$	**[m² / ha]**	**floor area of service-sector buildings per hectare cell**
$\boldsymbol{P_{ha}}$	[1/ha]	population per hectare cell
$\boldsymbol{NbrSum_{ESM}}$	[-]	Neighbour Sum of ESM built-up area (600m radius)
$\boldsymbol{NbrSum_{Soilsealing}}$	[-]	Neighbour Sum of EEA soil sealing (600m radius)

$\boldsymbol{GDP}$	1000 USD/ km^2 (fixed 2000)	UNEP Gross Domestic Product 2010
$\mathbf{ESM}_{\%}$	[%]	ESM built-up area coverage of hectare cell

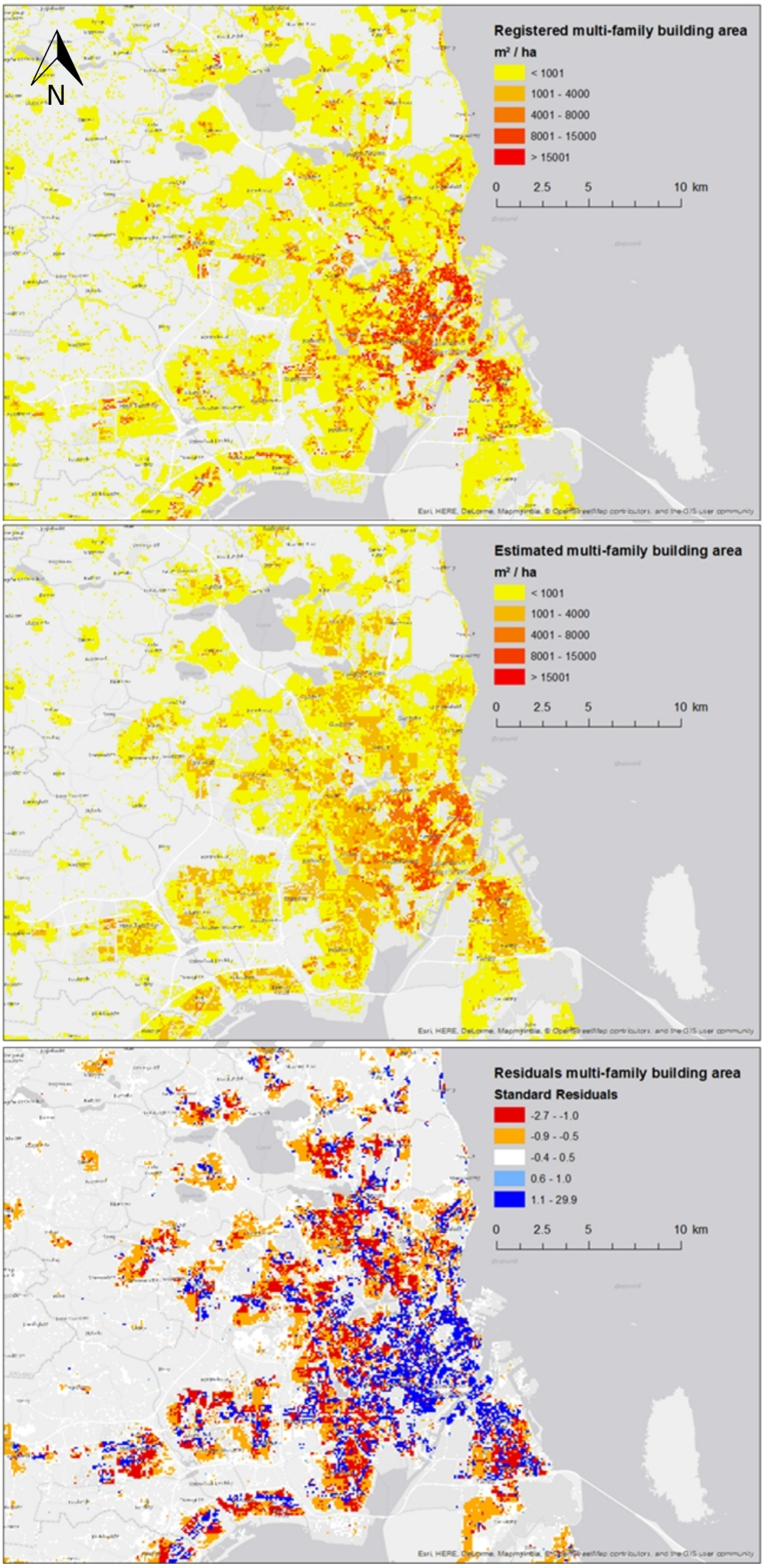


Figure 1: Estimation of residential sector floor areas – Multi-family houses: Actual (top) and modelled (middle) floor area densities as well as their standard residuals (bottom) of multi-family houses in the Copenhagen area

The regression formulae above are subsequently used to calculate the building floor area per land area, i.e. the plot ratio of single and multi-family and service sector buildings. The result is a pan-European quantitative geographical model of the built environment with a hitherto unprecedented spatial resolution and coverage, which subsequently would allow identifying heating and cooling demands, energy efficiency potentials, costs of district heating infrastructures, coherent supply areas, as well as a localisation of individual heat supply.

2.2. Calculation of heat demands

In the HRE4 project, national heat demands of the residential and service sectors are calculated using the FORECAST (FORecasting Energy Consumption Analysis and Simulation Tool) model at Fraunhofer Institute for Resource Efficiency and Energy Strategies (ISI) [36]. These heat demands are modelled for the base year 2015 on the national levels of the EU member states. The national heat demands are distributed to the hectare cells considering country-specific per-capita floor area derived from the Eurostat Census 2011 [37], the ratio of single- and multi-family houses and the specific annual heat demands of single-/multi-family houses and service-sector buildings from the FORECAST model. The European Heating Index [38] was used to create local adjustment factors that include climatic variations, socio-economic adjustment between demand and satisfied demand, as well as an area weighted index of population distribution.

The resulting heat demand grid has a total number of 40 million cells with heat demands greater than 0, corresponding to 10% of the land area of the 14 HRE countries. The integer grid consumes 4.55 Gigabytes disk space using the ArcGIS File Geodatabase format. For online purposes the heat demand grid was reclassified into a 2 bit raster of values 0 (< 50 TJ/km^2), 1 (50-120 TJ/km^2), 2 (120-300 TJ/km^2) and 3 (>300 TJ/km^2), whereby the amount of data has been reduced to a manageable 569 Megabytes.

2.3. Validation of heat demands

In order to validate the total heat demands, the heat demand densities and their geographical location, several validation strategies were developed. First, the total heat demands calculated were compared to the inputs to the model from the FORECAST model. Apart from rounding errors, the results were identical to the national demand, which shows that the model is consistent. Next, on the local level that is most relevant for the present model, heat demands are difficult to compare to existing demands. The reasons partly lie in the absence of recorded heat demand data, partly in the geographical reference used, which here is the 100m resolution grid. This resolution interferes with the actual address locators used in most countries, which means that depending on the kind of address system used, the location of buildings sometimes exceeds the limit of the single cell, and usually will place a large proportion of buildings at the margins of individual cells. The consequence of this is that a satisfactory comparison with address-located buildings is impossible. Instead, the location of heat demand relative to known boundaries of heat supply zoning, and the aggregate heat demand in these zones, has been compared to a recent Danish heat atlas using building-sharp heat demand data, [17], and current district heat supply areas [39].

The comparison between Peta 3, Peta 4 and the Danish Heat Atlas version 2 [38] shows almost identical results for the total demands, which were adjusted to area weighted shadow degree days for Denmark [40]. As Peta 3 was based on delivered heat demand, an adjustment factor of 0.8875 to final demand was applied, derived from the FORECAST data for Denmark, 2015. The result is striking as Peta 3 and in particular the Danish Heat Atlas have been designed using a completely different method and data base.

Table 7: Comparison of Peta 4 with Peta 3 and the Danish Heat Atlas version 2 [37] for Denmark. Heat demands (HD) are adjusted by degree days as the three models use different base years. It can be seen that Peta 3, Peta 4 and the Danish Heat Atlas assign very similar amounts of heat demand to areas with existing district heating or natural gas supply, comprising largely all built-up areas.

	Peta 3, 2010 [PJ] (adjusted to delivered heat demand)	Peta 4, 2015 [PJ]	Danish Heat Atlas version 2.7, 2012 [PJ]
HD in total	211	161	189
HD in supply areas	164	124	178
Degree day factor	113%	89%	100%
HD total, adjusted	187	181	189
HD in supply areas, adjusted	145	139	144
share of adjusted HD in supply areas	77.5%	76.8%	76.1%

2.4. Calculation of investment costs in thermal distribution networks

On the basis of the mapped heat demand densities, the present paper uses a method derived by Persson and Werner [41] and applied in Möller and Werner [8] to calculate the required investments in distribution networks for district heating and cooling. A forthcoming paper will describe updated and refined costs calculations for the HRE4 project in detail, and represent the final HRE4 project output.

The method assumes a uniform effective width and therefore the costs of distribution and connection pipes become a function of the demand density alone, see Figure 2. Cost data are based on the actual costs of Swedish district heating projects adjusted to price levels of 2014. Hereby it is implied that learning process effects, which may take place in the near future, have been considered for new district energy markets. Investment cost for district heating pipes per trench length are input to the model, as well as pipe dimensions and linear heat density as the main parameters. Small pipes are normally used in areas with single-family areas, with a high proportion of green areas. Wider pipes are normally used in inner city areas with higher building densities and higher construction costs. An empirically derived relation between the linear heat densities and the average pipe dimensions in 134 Swedish heat distribution networks or parts of networks, as presented in Frederiksen and Werner [42], is used. The linear heat density is the heat sold annually divided by the corresponding trench length.

Hereafter the relation between the average pipe dimension, at an effective width of 65 m, and the cost are found using empirical data from Sweden. The effective width is almost constant at that level for plot ratios above 0.4 [8]. The effective width is needed since the linear densities are equal to the product of the effective width and the land area densities. Finally, the specific average investment costs were estimated by dividing the average investment costs by the corresponding linear densities. The resulting cost function is shown in Figure 2.

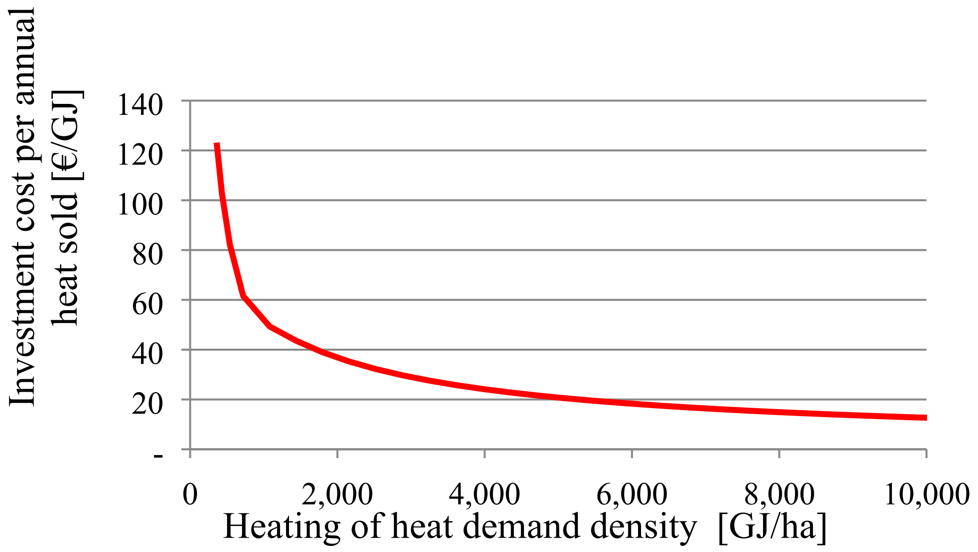


Figure 2: The specific investment cost per annually delivered heat as function of the heat demand densities, both related to the corresponding land area.

Derived from Figure 2 was a function of district heat distribution investment costs:

$$c = 4{,}924.8\ hdd^{-0.645}\ (R^2 = 0.9956) \qquad \textbf{Equation 4}$$

where *c* is the investment cost in district heat distribution networks in €/ha, and *hdd* is the heat demand density in GJ/ha.

This simplified model of district heat infrastructure disregards the actual layout of pipes, the number of consumers per area and other location-specific costs. Frederiksen and Werner [42] state that linear density (the annual heat sold by trench meter) is the decisive parameter in district heating networks, and linear density depends on effective width, which converges to a constant in most cases. This means that the actual pipe layout and the number of house connections can be disregarded in most cases; particularly where plot ratio (the ratio of floor area to land area) is higher than 0.3. It must therefore be stressed that the strength of this model lies in its simplicity and robustness, and any inclusion of other cost parameters may be difficult for a model on the European scale. The weakness and main source of error is the use of Swedish empirical data. It is however conceivable that economically and technically, Swedish district heating is at the bottom end of the learning curve, representing the benchmark costs of mature technology.

2.5. Modelling coherent supply areas

The aim of this paper is to achieve a localisation of heat demand and supply. For each 1 hectare cell in Europe it has to be decided whether it is feasible to invest in district heating, or in individual heat supply technologies such as boilers or heat pumps. Therefore, coherent areas of heat supply have to be identified. This may happen on the basis of cost efficiency, where the supply costs of infrastructure by cumulative demand are being mapped. However the full costs of a DH system include heat generation as well, so the extent of DH areas becomes a function of available low cost heat supply [22].

In the present paper, coherent supply areas are therefore mapped on the basis of physical conditions alone, as the economic evaluation requires feed-back on supply costs from energy systems analysis [2]. Accordingly, all areas with a heat demand density higher than 20 TJ/km² have been grouped to regions that are contiguous, i.e. composed of neighbouring cells. To collate contiguous areas of minimal heat demand, the RegionGroup tool in ArcGIS Spatial Analyst has been used. Double boundary cleaning was carried out to simplify the flossed boundaries of contiguous areas, and regions located within a buffer of 1 cell were merged to coherent regions less than 200m apart, as these may be part of the same supply area.

Besides disregarding investment and operation costs in DH systems, this method of delineating technical potentials for DH coverage does not take into account limitations rooted in socio-cultural norms such as individual preferences to heating systems [43]. Neither are any local or national restrictions such as technical norms and standards, planning regulations, conservation of historic places etc. included. The resulting prospective supply areas therefore are the minimum likelihood, maximum potential areas of heat supply, to which future heat supply may converge or not, given a successful implementation.

The extent of supply areas is here mainly (but not entirely) a function of the minimum desirable heat demand density, below which the development of district heating makes no sense. Usually the boundary of a heat supply area is more or less congruent with the boundaries of urban areas, although that heavily depends on the urban planning history, on urban sprawl and the criteria for contiguousness and continuity applied in the model. In order to avoid very large areas such as the Rhein-Ruhr area of Germany, the prospective supply areas were intersected with the NUTS3 layer to allow for smaller units, which follow a uniform administrative division across Europe.

The resulting supply area layer is used to summarize heat demands, to calculate cost-supply curves, and to present general statistics. It is above all useful to locate where district heating may ultimately be feasible, and demarcate the likely geographical boundaries of individual district heat supply areas. Table 8 shows the field codes of a table, which summarizes heat demands across Europe by prospective district heating system, administrative units, and by heat demand density. It also features a place name. Currently about 50,000 individual prospective supply areas are being mapped.

Table 8: Field codes of a table that summarizes heat demands (2015) by location relative to prospective DH system and administrative boundaries, and by heat demand density class.

OBJECTID *	generic ID automatically assigned
Shape *	geometry field, automatically generated
DHS_ID	prospective DH system unique ID
NUTS_ID	NUTS code, NUTS3 level
MS	EU member state code
HRE4_14MS	HRE4 country [yes/no]
Shape_Length	Perimeter in metres
Shape_Area	Area in square metres
Placename_assigned	Place name assigned from OSM
SumHD_0_20	Sum of heat demand in density class 0-20TJ/km^2
SumHD_20_50	Sum of heat demand in density class 20-50TJ/km^2
SumHD_50_120	Sum of heat demand in density class 50-120TJ/km^2
SumHD_120_300	Sum of heat demand in density class 120-300TJ/km^2
SumHD_morethan_300	Sum of heat demand in density class >300TJ/km^2

2.6. Generation of cost-supply curves for district heating systems

A cost-supply relationship is established by summarizing the potential of district heating for each instance of marginally increasing costs. Potentials equal here the final heat demand see chapter 2.2, while costs are the investment costs in district heating infrastructure, see chapter 2.4.

Cost supply curves are being prepared for countries, regions, or individual prospective supply areas. In order to do so, a spatial analysis approach summarizes heat demand values for each instance of integer cost values and for each supply zone. The result is a tabular expression of cumulative heat demands by marginal or average investment costs necessary to transfer the heat. Figure 3 shows an example for such a cost-supply curve.

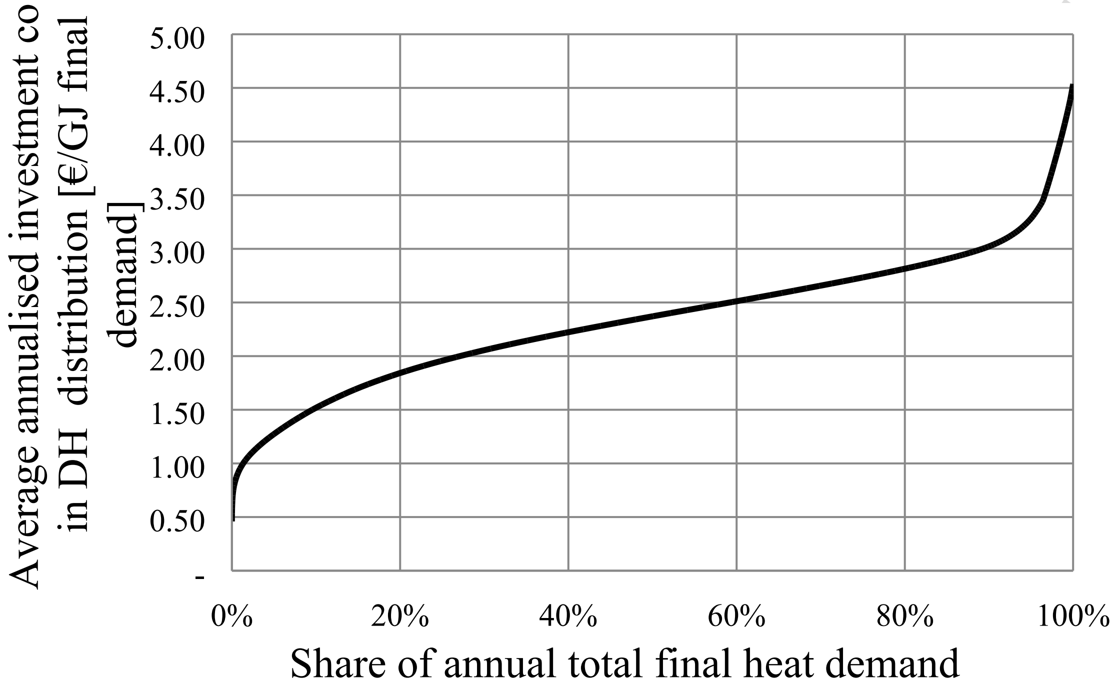


Figure 3: Cost-supply curve (example) of district heating distribution infrastructure for the UK. Cost-supply curves establish an analytical relation between a quantified potential of district heat development and the associated marginal costs. They are important for separating the economic from the technical potential.

3. RESULTS

Heat demands for the year 2015, the investment costs of district heating systems, and a delimitation of prospective heat supply areas have been modelled.

3.1. A Pan-European map of heat demands 2015

For all HRE4 countries the heat demand in 2015 was mapped. The total heat demand was derived as the sum of single-family residential, multi-family residential as well as service sector heat demands, all of which include the consumption of hot water. The result is a layer for all of Europe, which forms the basis of calculations of investment costs in district heating, investment and operation costs of individual heat supply units, and the delineation of a heat supply zoning map. Furthermore, the heat demand densities have been reclassified into categories of heat demand densities for a quick assessment of the feasibility of district heating systems following the Danish Energy Agency technology catalogue [44].

The resulting heat atlas (see Figure 4: Total heat demand in 2015 for the Brussels area. The 100m resolution represents very well the urban structure. The intervals of heat demand density are suggested by the Danish Energy Agency and they represent the degrees of feasibility of district heating systems.Figure 4) gives a very strong image representation of the current heat demands in Europe. It also is a powerful analytical basis for assessments of demands and for the formulation of supply strategies.

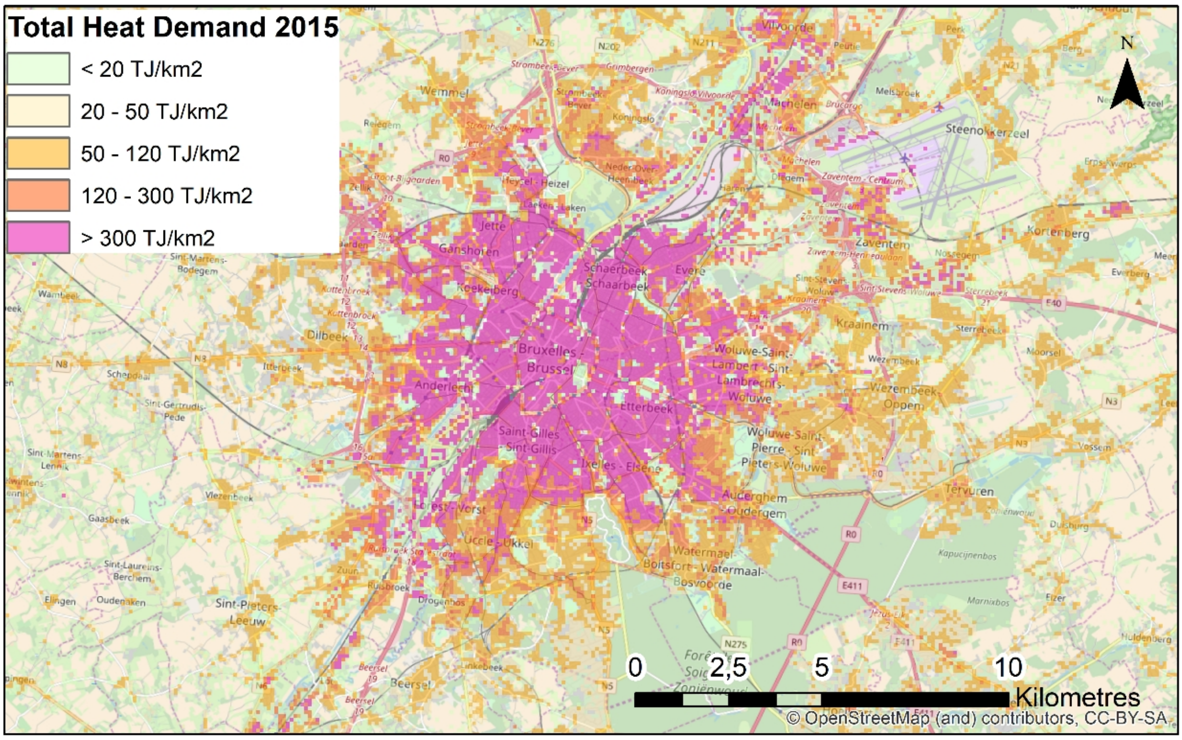


Figure 4: Total heat demand in 2015 for the Brussels area. The 100m resolution represents very well the urban structure. The intervals of heat demand density are suggested by the Danish Energy Agency and they represent the degrees of feasibility of district heating systems.

3.2. A Pan-European map of heat supply zoning

Using the approach presented in chapter 2.5, a geographical division of all of the HRE4 countries into coherent supply areas with preference (on the basis of heat demand densities, DH grid investment costs and distance) was generated. This zoning has applied across member state boundaries as there are several border areas where the establishments of cross-border heat supply may be feasible. Figure 5 shows a heat supply zoning map prepared for the city of Aarhus in Denmark, where also the known boundaries of existing district heat supply installations from the national planning data portal Plansystem.dk [39] are shown.

It can be seen that with the exemption of industrial estates and very small settlements, the present heat supply zoning model accurately replicates the outer boundaries of areas, where district heating would be feasible and likely under the Danish regulation. Very small settlements are presently excluded, while industrial estates are not part of the model as industrial heat demand is presently not part of the heat atlas. With the heat atlas at hand, several extracts can be made for administrative units and for several variables such as heat demand density, see Table 9.

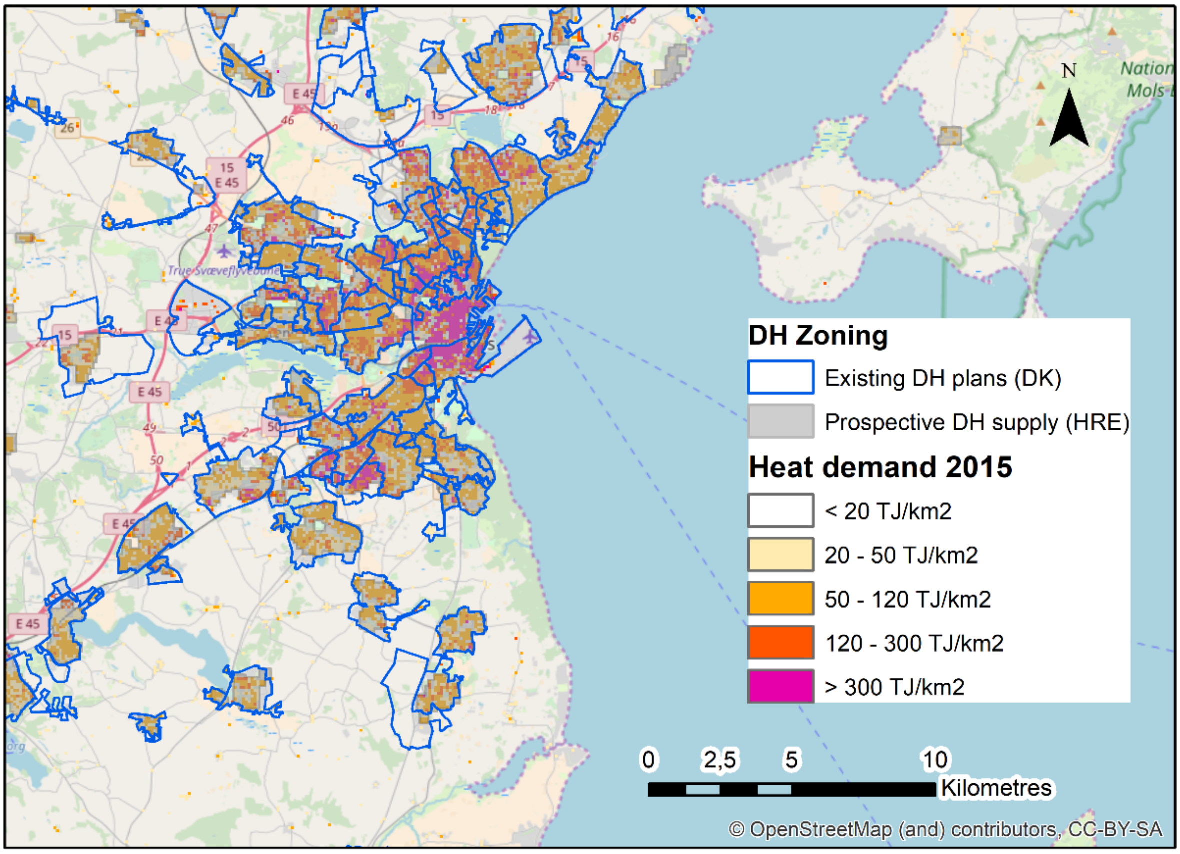


Figure 5: Heat supply zoning map for the city of Aarhus, Denmark, including actual and existing district heat zoning. The Urban and Semi-Urban zones largely follow the existing zoning in Danish heat planning.

3.3. A pan-European assessment of the costs of developing district heating

For all 14 HRE4 countries cost-supply curves of average annualised costs per share of total final heat demand are shown in Figure 6. It can be seen that district heating can be propagated in these countries at widely different costs. While in Italy and Spain, 66% of the total final heat demand can be covered with average annualised distribution investments of 2.00 €/GJ final heat consumed, in the Netherlands and in Germany at this cost the share would be 50%, while most other countries reach shares between 27% and 43%. Romania and Hungary are exceptionally costly to develop, assuming the same specific costs as for all of Europe.

Cost-supply curves also tell about the cost sensitivity. A country like Poland shows a higher sensitivity of the utilised potential to costs than e.g. Italy, as can be seen from the steeper curve. A major limitation in the present model is that costs in all countries have been calculated using the same cost function, which alone is related to heat demand densities. In earlier studies [41, 45] and in particular in a recent review by Werner [3] the uncertainties of this approach have been addressed. Because heat demand densities, apart from climatic and socio-economic reasons, largely depend on the density of the built environment, the cost-supply curves directly relate to the way cities, towns and villages are built up.

Table 9: Heat demands [PJ] for each EU member state, by heat demand density.

HRE4 country	< 20 TJ/km^2	20-50 TJ/km^2	50-120 TJ/km^2	120-300 TJ/km^2	> 300 TJ/km^2	Total
AT	40.17	55.80	70.33	32.80	29.21	228
BE	31.44	65.28	150.12	41.86	30.86	320
CZ	35.34	60.28	64.21	47.38	26.52	234
DE	260.75	295.21	927.24	627.93	268.95	2,380
ES	71.37	74.14	89.16	116.07	102.64	453
FI	61.94	39.24	70.89	37.55	11.09	221
FR	272.53	408.41	461.97	186.86	156.90	1,487
HU	27.87	113.39	40.90	18.03	7.35	208
IT	165.11	151.77	318.14	408.37	213.18	1,257
NL	43.23	34.77	164.47	136.05	38.86	417
PL	126.83	223.24	145.08	108.75	43.68	648
RO	92.89	39.90	23.94	20.86	3.74	181
SE	69.00	56.86	84.26	50.42	29.26	290
UK	91.83	112.47	752.34	331.21	45.83	1,334

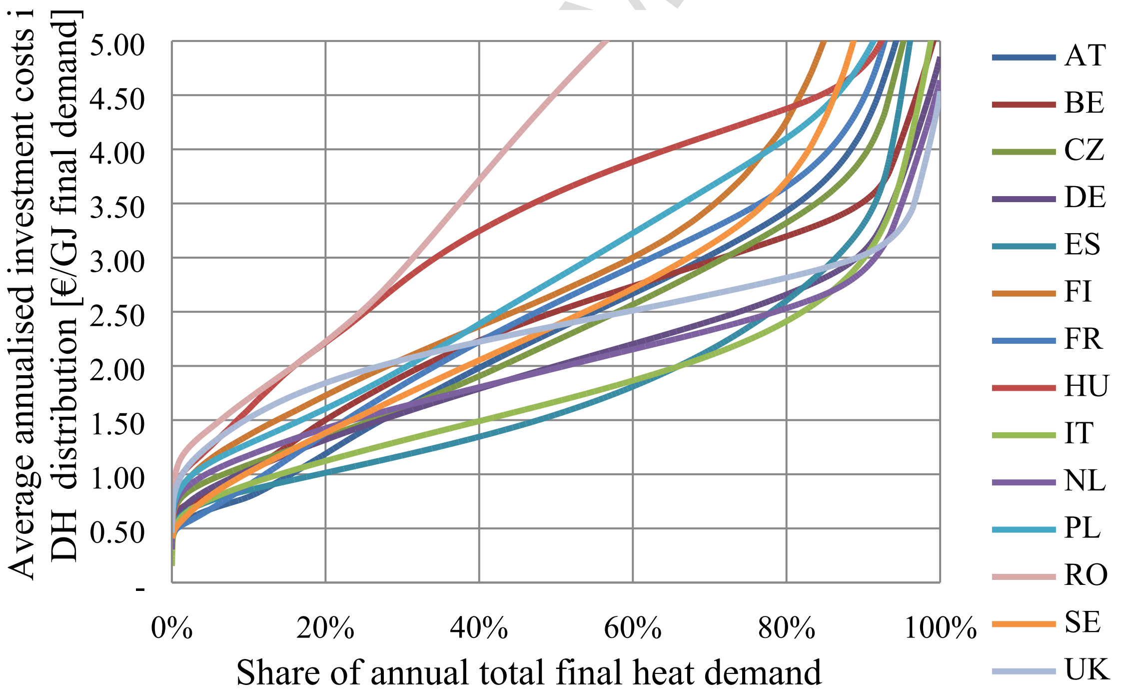


Figure 6: Cost-supply curves of average annualised investment costs in district heat distribution infrastructure for cumulative shares of total final heat demand in the 14 HRE4 countries.

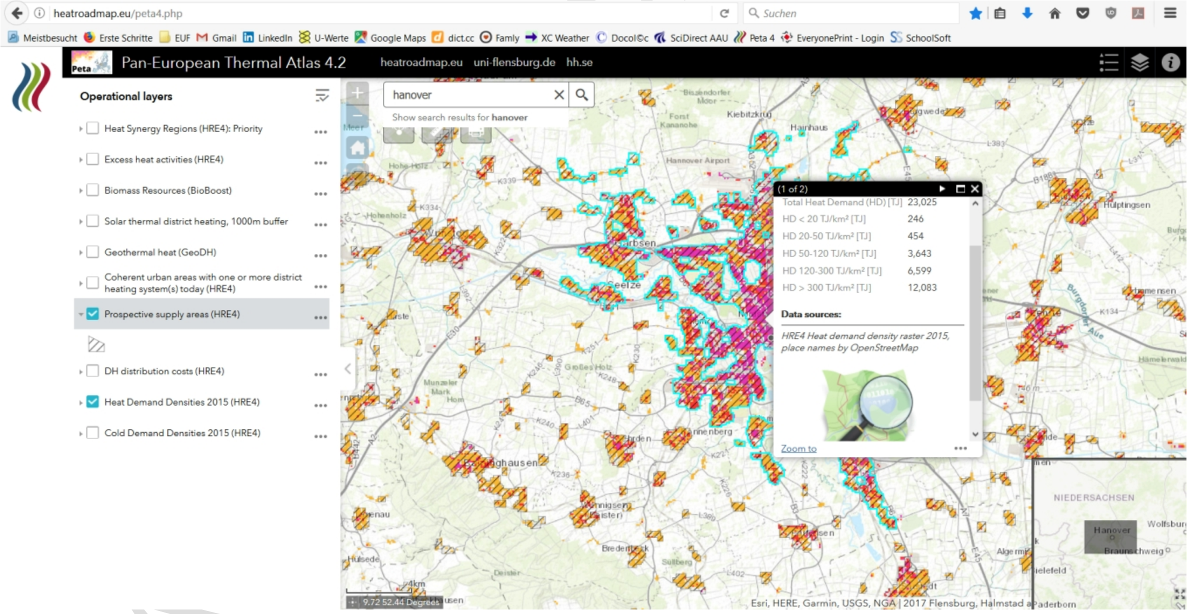
4. DISSEMINATION THROUGH AN ONLINE MAPPING PORTAL

The magnitude and multitude of generated data for heat demands, prospective heat supply areas, and development costs necessitates an efficient means to publish and disseminate the information contained. Internet-based mapping allows for this, as it basically provides access to visual examination, analysis and data sharing with a global audience. As the Internet-Mapping platform for the present HRE4 project, ArcGIS Online was chosen. Data were uploaded to a mapping portal hosted at the Environmental Systems Research Institute (ESRI), web maps were created and a web mapping application was developed, which allows for the visualisation of heat demand 2015, excess heat activities, present district heating systems (from the Halmstad University District Heating and Cooling database, HUDHC) as well as summarized heat demand by prospective district heating system and by heat demand density class.

Figure 7 shows a screenshot of the online Peta4-atlas developed as a web mapping application within ArcGIS.com. The example shows the area around Hanover, Germany, where the heat demand density is shown along with data from the HUDHC database, an excess heat activity layer, and the summary of heat demands by heat demand density for prospective heat supply areas that also can be seen in the map.

Several features such as HUDHC database information, summaries of heat demand, and excess heat activities can be accessed by pop-up windows. The online map has added functionality for location of place-names, for printing and for sharing with social networks.

As it is impractical to visualise the resulting online heat atlas in printed media, it is being referred to the Peta 4 Online atlas at http://www.heatroadmap.eu/Peta4.php. A user guide [46] is available at http://www.heatroadmap.eu/resources/D2.4%20website%20version.pdf



- ☐ Heat Synergy Regions (HRE4): Priority
- ☐ Excess heat activities (HRE4)
- ☐ Biomass Resources (BioBoost)
- ☐ Solar thermal district heating, 1000m buffer
- ☐ Geothermal heat (GeoDH)
- ☐ Coherent urban areas with one or more district heating system(s) today (HRE4)
- ☑ Prospective supply areas (HRE4)
- ☐ DH distribution costs (HRE4)
- ☑ Heat Demand Densities 2015 (HRE4)
- ☐ Cold Demand Densities 2015 (HRE4)

(1 of 2)

Total Heat Demand (HD) [TJ]	23,025
HD < 20 TJ/km² [TJ]	246
HD 20-50 TJ/km² [TJ]	454
HD 50-120 TJ/km² [TJ]	3,643
HD 120-300 TJ/km² [TJ]	6,599
HD > 300 TJ/km² [TJ]	12,083

Data sources:

HRE4 Heat demand density raster 2015, place names by OpenStreetMap

Zoom to

Figure 7: Screenshot of Peta 4 online web mapping application developed by means of ArcGIS.com.

5. DISCUSSION AND CONCLUSIONS

A Pan-European Thermal Atlas has been developed further, which can be used to quantify heat demand and the potential for district heating in order to assist in the preparation of heat supply strategies and plans on national, regional and possibly local scales.

First, a model of floor area distribution by sector was developed, at a hitherto unprecedented scale and resolution of 1 hectare per cell. A geostatistical model establishes a relation between readily mapped phenomena like the percentage of built-up areas, population distribution and the built environment in order to model plot ratios of single and multi-family as well as service sector buildings. Using forecasted heat demand data on national levels, heat demand was spatially disaggregated to 100m cell size via these plot ratios. This formed the basis for a calculation of investment costs in district heat distribution infrastructures, to be used to generate cost-supply curves that comprise an analytical relation between the technical and the economic potential of district heating. Next, a spatial model was developed, which allows for the delineation of prospective district heat supply areas. These are areas where district heating may be developed taking into account increased shares of renewable energy, energy efficiency and lower network temperatures [47]. Such areas will follow the design principles of 4th generation district heating (4DH) [47, 48]. Finally, heat demands in rural areas, where individual heat supply technologies would be the preferred option, can be quantified. This way, Peta in its 4th version represents a coherent model of heat demand and supply options with a sufficiently high spatial resolution to locate single prospective supply areas, for which the main parameters for heat demand and supply, potentials and costs, can be generated.

Compared to its predecessor Peta3, the present version Peta 4.2 has been improved in several ways. First, by including ESM and the 100m population grid of the JRC, better coefficients of correlation have been realised compared to the previous version, which had to rely on the older soil sealing layer by the EEA, which had to be modified to remove roads; as well as a disaggregated population grid, where population at 1km^2 was disaggregated using a modified soil sealing layer. The new datasets have resulted in a smoother heat demand map, which depicts urban structures better than the predecessor Peta3.

The present model has been developed using building data from Denmark, where a national building register exists, which contains building-sharp physical data of the built environment. These were used to train the multiple linear regression models, whose dependent variables were the registered and known floor areas of single family, multifamily and all buildings. Coefficients of determination were low on the 100m resolution, and moderate to very good when resampled to 1km resolution. Multi-family buildings were found easier to model than single family buildings and especially of service sector buildings, and it was realised that this does not necessarily mean an inferior model of low-rise residential areas because over larger extent these areas were more uniform.

Heat demands in 2015 for room heat and hot water were then distributed to the 100m grid, using per-capita heat demands and the plot ratios of single- and multi-family buildings. Service sector heat demand was distributed to bottom-up generated plot ratios, as national data on building area does not exist. The resulting heat demand model is so far the most detailed and extensive of its kind. It is emphasised that it is a model, where representativeness is more important than a precise account for actual heat demand distribution within neighbourhoods. The validation against national data shows no deviation, and the comparison with the Danish Heat Atlas version 2 [38] confirms that heat demands are actually very accurately located within areas of district heat and natural gas supply. It may therefore be concluded that the method is applicable to delineate prospective supply areas.

On the basis of heat demand density at 100m resolution, the investment costs in district heat distribution infrastructure were calculated using a single cost function. The sole input to this cost function is the heat demand density. The combination of distribution investment costs and heat demands allows for the calculation of cost-supply functions for individual prospective supply areas. These cost-supply functions are a means to separate the economic from the technical potential for given marginal or average costs of utilising a cumulative heat demand resource.

The paper has presented a novel way of zoning the geographical delimitation of heat supply. This zoning may represent the boundaries between district heating and individual heat supply, which apart from heat demand densities are a function of the energy policy and regulation in a given country. Taxation, mandatory planning and zoning, organisation and ownership may all influence this boundary, leading to a technology-wise separation of heat supply into several individual types of heat supply, like heat pumps and boilers, as well as several types of district heating, for example 3rd or 4th generation district heating [48].

Finally, an economic appraisal of the heat supply options by technology, location, and costs can be carried out for all political, administrative or arbitrary regions. Areas with large, coherent and interconnected district heating can be identified, but also those areas, where individual heat supply technologies should be preferred.

Future work will include the mapping of renewable thermal energy sources such as solar and geothermal heat. Biomass fuels may be quantified on the basis of data from the EU Bioboost-project [49], focusing on residues from forestry and agriculture as well as biodegradable household waste. Excess heat from industry, power generation and waste incineration has been quantified and mapped on the basis of least costs [23]. Future studies will include an allocation of limited excess heat potential to the nearest prospective DH supply areas in order to achieve a least-cost match between demand and supply. The result will be a coherent and comprehensive map of European heat demand and supply, which can be used in subsequent research within the Heat Roadmap Europe project to perform advanced energy systems analysis and to prepare national heat supply strategies.

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Research highlights

- The first ever pan-European atlas of heat demand at 100m resolution
- Delineation of up to 50,000 individual prospective heat supply areas
- Calculation of district heat distribution investment costs at 100m resolution
- Preparation of cost-supply curves to separate economic from technical potentials
- Online mapping and dissemination tool to study local heating strategies