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Mapping the Heating and Cooling Demand in Europe

Work Package 2

Background Report 5

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4DH
4th Generation District Heating Technologies and Systems

STRATEGO Website: http://stratego-project.eu
Heat Roadmap Europe Website: http://www.heatroadmap.eu
Online Maps: http://maps.heatroadmap.eu

Heat Roadmap Europe 2050

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1. Mapping the Heating and Cooling Demand in Europe

Mapping the heating and cooling demand is a basic requirement and precondition for the formulation of energy policies as well as the implementation of directives that aim at the integration of energy systems by means of efficiency in end use and supply as well as renewable energy. It is required for the analysis of expansions of major energy infrastructures like gas or electric grids. Although the main focus in this project is the development of district heating and cooling systems, a thorough knowledge of the location and intensity of heating and cooling demands, as well as the efficiency potentials greatly facilitates the formulation of sustainable energy development policies and their follow-up measures.

Studies of the potentials of developing district heating and cooling (DHC) grids require a geographically explicit quantification of heating and cooling demands (Persson et al., 2014). The high costs of distribution networks, the investments in heat and cooling transmission, as well as the geographically determined sources of district energy require heating and cooling demands to be mapped. Further, while seeking to increase the energy efficiency of the built environment, the present location and amount of final energy demand cannot be granted. Finally, trends of urbanization and structural change make the location and distribution of heating and cooling demands even more interesting.

In previous studies (Connolly et al., 2013; Gils 2012) the potential for developing DH schemes was assessed using small-scale statistics as well as geographical representations of heating demands at a spatial resolution of $1km^2$, typically using a distribution of heat demand on population and specific land use. But within one km^2 the typical urban tissue of towns and cities varies, and smaller settlement structures disappear. Hence the actual geometry of district energy grids, their cost-determining densities and the connectivity between grids cannot be represented to a degree, which is needed for improved potential and cost assessments beyond the 1km resolution. While avoiding the Modifiable Area Unit Problem (Openshaw, 1984), which occurs if statistics are compared by using variable geographical entities, and offering a practical scale of analyses on the European level, the 1km2 grid studies did not allow for a precise delineation of DHC systems because most urban and semi-urban settlement structures show high variability within one square kilometer. Neither are they suitable for local and regional studies.

DHC distribution infrastructures follow the building and population distribution. Heating and cooling demand, within a country and for the residential sector, are the function of available building area per capita and specific thermal demand per area. Therefore, knowing these ratios, heating and cooling demand can be mapped taking departure in the location of buildings. Mapping the building matrix of all member states of the European Union in a limited study like the present necessitates a simple yet robust tool. The present Pan-European Atlas of sub-$1km^2$ resolution attempts to distribute the demand for cooling and heating in residential and service sector buildings on such a small scale, that the delineation of actual DHC grids becomes feasible. Along with demands the costs of such systems are being mapped in the same geographical entities, so that studies of marginal costs of a cumulative supply of thermal services become feasible. This has been realized on a smaller scale for Denmark (Möller and Nielsen, 2014), and has been attempted without a spatial explicit model of DHC demands in Europe (Persson and Werner, 2011).

A basic hypothesis is that district heating and cooling can be developed everywhere, where there is a sufficiently high demand density. All demands below a given threshold could be supplied at lower costs compared to individual heating and cooling solutions. So far, with the exemption of Denmark, Sweden and Finland, where more than half of the heat demand is covered by collective systems, most heat demand seems to be out of reach for such systems. Collective cooling systems do only exist in a few places yet. At the same time, assuming empirical cost data from the Scandinavian countries, somewhat near-optimal system designs and costs can be assumed and transferred to the rest of Europe.

Mapping of heating and cooling demand is the precondition to describe the possible supply and its costs for all urban areas (cities, towns, suburbs as well as villages larger than 1-2 km^2 and typically exceeding a population of 200. Furthermore, the agglomeration of such prospective DHC systems is to be analyzed, as there are economies of scale but also limitations of transport distances prevailing in this kind of studies.

1.1. Objectives

For the 5 target countries (CZ, HR, IT, RO and UK) the heat demand in residential and service sector buildings is to be mapped. Cooling demands are to be mapped for service sector buildings. Mapping is done on a sub-1km2 basis, which means that gridded data down to the 100m resolution are used to better describe what happens within the 1km scale, which is the output resolution for all subsequent studies. Publicly available geographical data compliant to the EU INSPIRE directive is to be used to the widest possible extent.

1.2. Method

Raster-based Geographical Information Systems (GIS) are used to model and map heating and cooling demand as distribution functions of population, land use and soil sealing in a combined top-down and bottom-up manner. National energy statistics, combined with small-scale statistics on the NUTS3-level are used to calculate specific or absolute heating and cooling demand values on a per-capita (heat) or per-m^2 (cooling) basis. Where HRE2 used a 1km resolution for the analysis, the computational basis used in the Stratego project is the 100m resolution, at which several publicly available datasets exist, which represent the small scale geography of urban areas. The results are re-aggregated to the 1km scale.

In the case of heat demand, population density per 1 km^2 is distributed to population densities per hectare (ha), derived by multi-linear regression modelling from a 1km^2 population grid as well as geographical data that describes the qualitative and quantitative pattern of settlements. Cooling demand is more complex to model because of several basic differences from heat demand. Firstly, a large part of the theoretical cooling demand is and will remain to be unmet, resulting in a cooling demand and a cooling consumption value for a specific building. Then, cooling demand currently mostly happens in service sector buildings such as shops and offices, whose locations cannot be mapped specifically on a European scale. The statistical model is therefore vital to find the likely distribution of service sector building areas within urban areas.

ArcGIS version 10.2.1 with Spatial Analyst was used to carry out the extensive analyses in the raster domain. All calculations were done using Model Builder, which is the graphical modelling interface in ArcGIS. All results were saved to a file-based Geodatabase. ArcGIS in its latest version is OGC-compliant, i.e. it follows the recommendations of the Open Geospatial Consortium Inc. for GIS interoperability, which allows users to "access data and services from many different sources, regardless of the technology used by those sources. In addition, users can share their content with others, including non-Esri users, thus contributing to the larger goals of the open data movement." (GeoCommunity, 2015).

1.3. Data input

Three central data themes form the data basis for representing the geographical distribution of heating and cooling demands within the European heating and cooling atlas. First, the population is mapped using the GEOSTAT 2011 1km population grid (GISCO, 2014). Second, the urban tissue is mapped qualitatively using Corine 2006 land use grid with 100m resolution (EEA, 2014a), while a quantitative measure for urban land use is the degree of soil sealing, mapped by the European Environment Agency at a 100m resolution grid (EEA, 2014b).

As a general spatial reference, a 1km grid by GEOSTAT (Eurostat, 2014), which is INSPIRE-compatible (IINSPIRE, 2014) and which uses the ETRS89 datum and a Lambert Azimuthal Equal Area projection to maintain area representation.

Additional data used is a NUTS3 administrative boundary layer originating from ESRI's ArcGIS Online service (ESRI, 2014), which had to be adjusted to the 2010 Eurostat data used in Background Report 6, plus the Open Street Map background layer service via ArcGIS (OSM, 2014).

Hence, all data used for distributing heat and cooling demand are either publicly available, owned by public institutions or the public domain.

1.4. Analysis of urban tissue: land use, settlement density and energy demand

An initial analysis was carried out to see if there is a spatial relation between land use and settlement density expressed by, among others, soil sealing. Soil sealing is mapped by the EEA and defined as the degree of imperviousness of surfaces, using a scale from 0 - 100% within a given geographical unit, here 1 hectare (ha).

By geo-statistically overlaying land cover and soil sealing it can be seen in Figure 1 that there is a close relation between soil sealing and urban land use associated to built-up areas, in particular the CORINE land cover classes 111 (Continuous urban fabric), 112 (Discontinuous urban fabric) and 121 (Industrial or commercial units). More than 90% in average of all soil sealing happens in urban built-up areas.

Within the 1 ha resolution, most details like the distribution of buildings and other sealed surfaces like roads etc. in smaller cities and in fringes of larger metropolitan areas would be leveled out by the coarse raster resolution. The overall urban structure, given by the boundaries to the lesser developed and green areas, is represented very well by the soil sealing grid, and explicitly by the land cover grid. It is here assumed that the population accounted for within a 1km2 raster cell is distributed only to the cells of 1 ha resolution, which have urban land cover (CORINE codes 111 and 112). Furthermore it has been assumed that the distribution of people follows the distribution of soil-sealing. Because the actual distribution between building footprint area and other sealed areas is different from one city to another, and from country to another, and specific heat demand is a function not only of the population density, but also building qualities and the available floor area per capita, the distribution has to be adjusted to actual data using small-scale statistics, see Background Report 6.

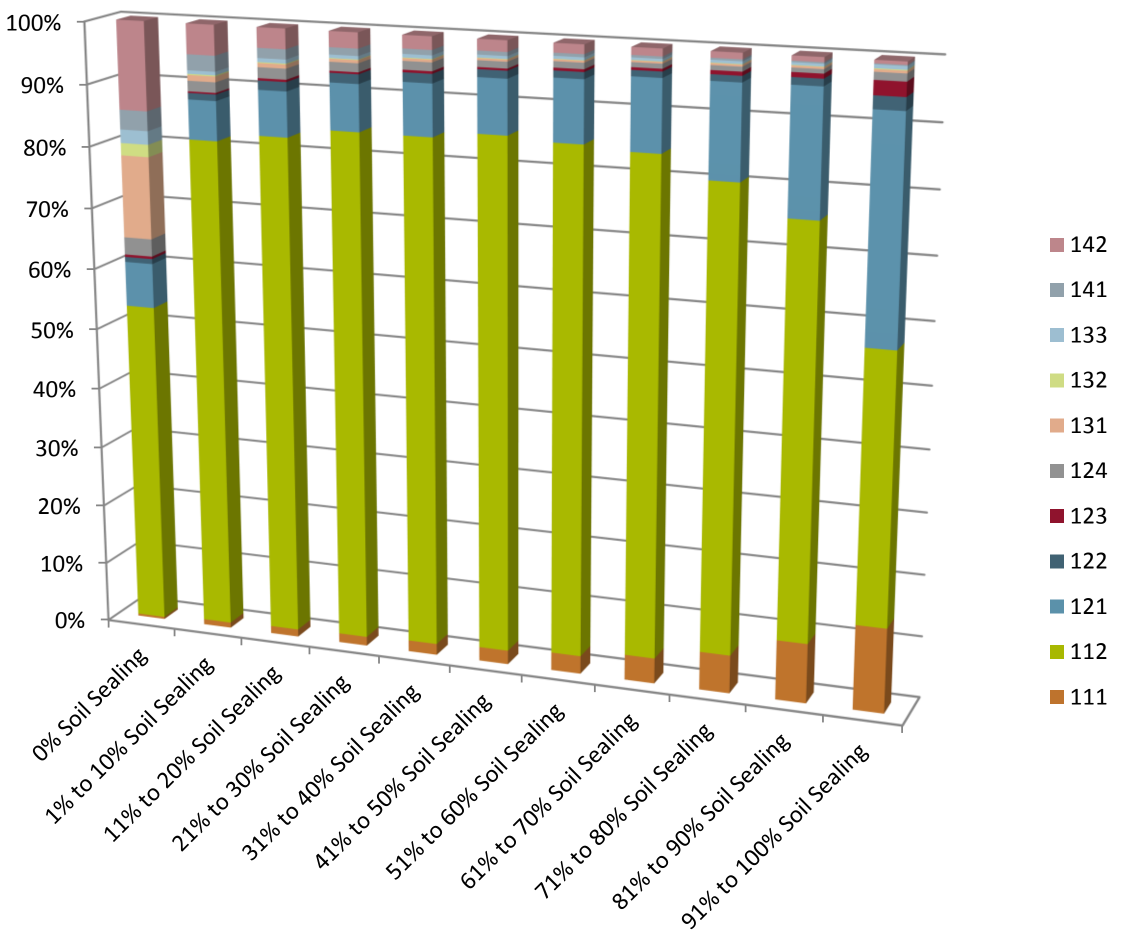

Figure 1: Percentage of CORINE land cover classes for bands of soil sealing. It can, among others, be seen that the urban land use class 111 (continuous urban) predominantly is featuring high percentages of soil sealing.

1.5. Heat demand model

Heat demand in buildings of the residential and service sectors are mapped separately. While the distribution of residential heat demand is assumed to be proportional to population, service sector heat demand typically can be located looking at urban functions.

First, the population represented by the GEOSTAT 2011 grid was distributed to 100m resolution. This is done using soil sealing as a proxy to the intensity of the built environment, which again follows population density. A regression done for the Netherlands shows the following relation between soil sealing and population (PDOK, 2015) it shows the average population density for each degree of soil sealing, see Figure 2. Please observe the values of the standard deviation also, which tell that in low and high density areas the deviation is higher.

According to the results for the analysis of urban tissue above, from the CORINE maps the land cover codes 111 (Continuous urban fabric), 112 (Discontinuous urban fabric) and 121 (Industrial or commercial units) were extracted to exclusively map built-up areas. Within these, as a proxy for building density the degree of soil sealing was used.

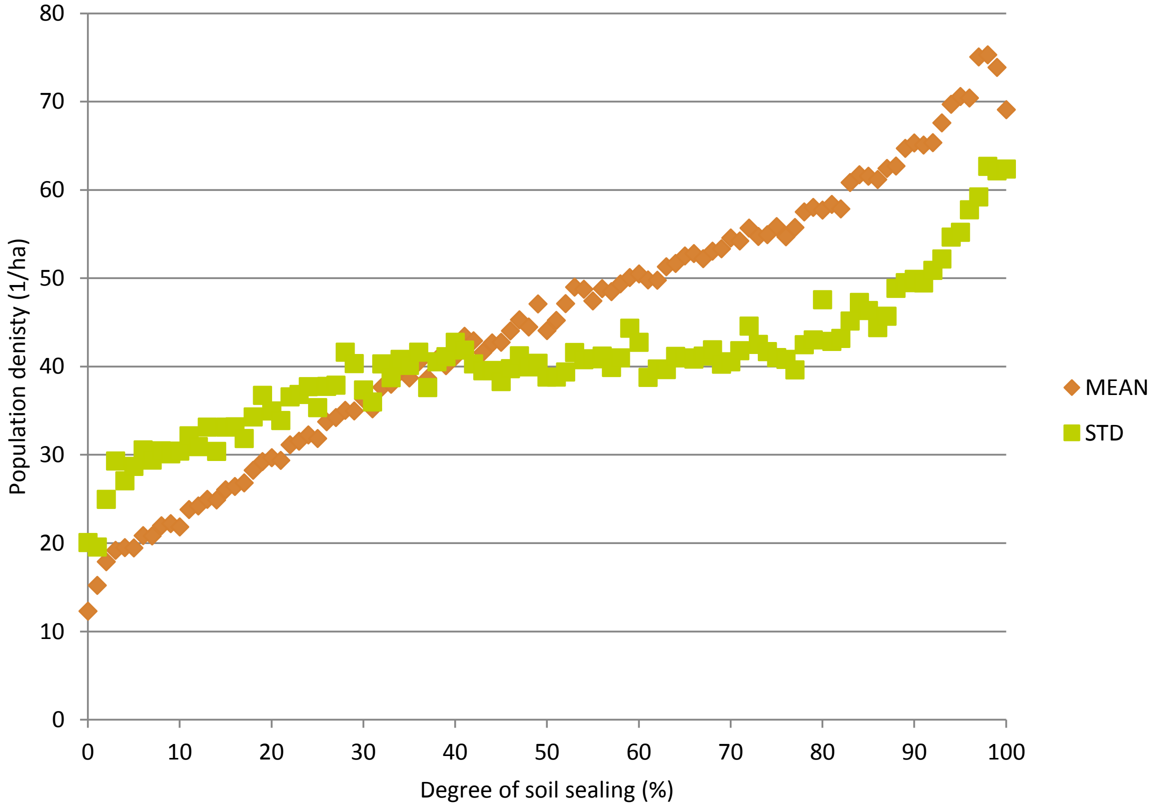

Figure 2: Average population density by degree of soil sealing for the Netherlands, where 100m population data is available.

As there are other urban land cover types with high degrees of soil sealing, such as roads, parking lots and public places, which may be larger than 0.5 to 1 ha and therefore show in a 100m grid, some adjustment has to be made. To remove linear structures such as roads, boundary cleaning was used, see Figure 3. The boundary cleaning was used twice. It also was effective at removing smaller groups of 1-4 cell clusters, which may represent larger non-built-up areas. The evaluation of effective removal of roads etc. was based on a spot checks in several urban areas followed by comparison to aerial photographs (various sources, ESRI).

To distribute population over built-up areas, population in a 100m cell is calculated multiplying the ratio of soil sealing in a 100m cell and the sum of soil sealing in a 1km cell with the population count per 1km cell. The result is an approximation of real population density, assuming that the population of the GEOSTAT grid lives in the above mentioned land use classes only. When re-aggregating the final results to 1km grid size, the original population and therefore heat demand is maintained, only the heat demand densities are adjusted to a better distribution of the built environment.

Figure 3: Effects of boundary cleaning of the soil sealing layer in Boolean prepresentation (left). The layer on the right hand side shows only the larger compounds of areas with urban development. The sealed road surfaces, which are visible in the original layer, as well as smaller built-up areas, are removed. The sample is from the Derby area, UK.

Residential heat demand for the 100m resolution model is modelled using the per-capita heat demand data on the NUTS3 level, see Background Report 4, using the population per 100m cell.

Service sector heat demand is modelled using a calculated plot ratio of service sector buildings. The plot ratio accounts for the building area per ground surface area. It is modelled using an ordinary least square statistical model, which applies three variables found by experiment using real building densities from the Danish heat atlas (Möller and Nielsen, 2013): population density has an influence on service sector density because it is assumed that services are located in the proximity of population, which is however not the case for very large office districts, such as parts of the city of Paris, or extensive shopping areas near large cities. Second, the degree of soil sealing reveals patterns of urbanity, which also is assumed to be related to the occurrence of service sector buildings. Thirdly, the average soil sealing density within a defined neighbourhood of 300m is another variable with influence on the service sector plot ratio. The resulting multi-linear regression model and its parameters are shown in Table 1. The overall adjusted R^2 value is 0.097, which seems very low, but if the resulting plot ratios are re-aggregated to 1km resolution, the R^2 becomes 0.616, which is very acceptable. This shows that the uncertainty lies in locating the actual service sector buildings exactly within the 100 possible 1-hectare cells of a 1 km2 grid. Here the model can only place 10 out of 100 cells correctly; placing the remaining cells almost at random. Comparing the 100m model with the actually registered buildings in Denmark it can be observed that the plot ratio is somewhat lower, hence the plot ratio and hereby the heating and cooling demand densities predicted are conservative.

The model has low standard errors, the probability and robustness values show highly significant p-values ($P < 0.01$). Low Variance Inflation Factor (VIF) values (< 7.5) indicate low redundancy among explanatory variables, even though soil sealing above 87% and the neighbourhood mean soil sealing are closely related, but that does not seem to have an effect on the small geographical scale applied here.

Table 1: Results from the multiple linear regression model of service building areas.

Variable	Coefficient [a]	StdError	t-Statistic	Probability [b]	Robust_SE	Robust_t	Robust_Pr [b]	VIF [c]
Intercept	-19785	193032	######	0.000	1917	-10.35	0.000	-------
POP	31.167	1.612	19.32	0.000	1.654	18.84	0.000	1.086
SOILSEAL	228.96	21.04	10.87	0.000	22.05	10.38	0.000	1.108
GRIDCODE	46.672	5.133	9.091	0.000	6.079	7.678	0.000	1.197

As the model is based on the relations between population and soil sealing in Danish towns and cities, the resulting sums of building areas in the service sectors need to be adjusted for other member states to result in appropriate geographical distributions of service building areas. This is done using the data from Figure 13 in Background Report 4.

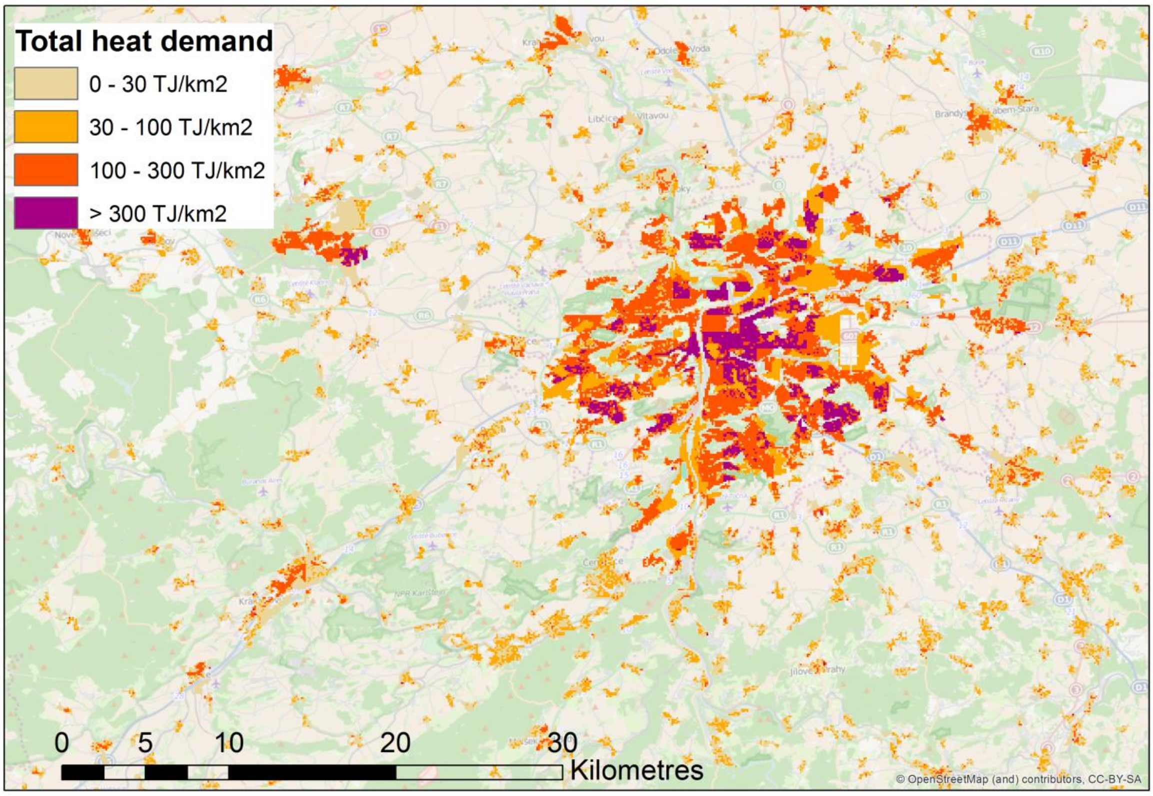

Figure 4: Extract from the 100m Heat Atlas showing heat demand in the Prague area, Czech Republic.

Using the model coefficients from Table 1, the service sector plot ratio is calculated for all EU28 member states and used to model the service sector heating and cooling (see below) demands. Finally, residential and service sector heat demands are added. The outcome is a heat demand map of 100m resolution, in GJ/ha or GJ/cell. It can be seen in Figure 4 how well the geographical delineation of towns and cities is replicated. However, great care has to be taken in using the data on a very local scale as the model only suggests high accuracy of this hitherto unprecedented scale. Nevertheless, the authors believe that the resulting Pan-European sub-1km Heat Atlas may be a further development of the 1km heat atlases of the

Heat Roadmap Europe Pre-study 2 as it better represents the geography of heat demand and collective heat supply areas.

1.6. Cooling demand model

The basis for calculating cooling demands form the statistics of service sector area and the European Cooling Index (ECI), see Background report 4. For the distribution of cooling demand the service sector plot ratios developed in the previous section are used, which are multiplied with the ECI values (in kWh/m^2).

It can be observed that service sector buildings and their cooling demands are confined to smaller areas predominantly in urban centres. The areas are often less coherent than the prospective district heating areas. Therefore great care has to be taken to model the potentials and costs of district cooling.

The cooling demand model is a first, rough estimate. First, the ECI values are based on average building efficiency and intensity of use. Second, the distribution of the service sector buildings is based on statistics from Denmark only, which is a small country where zonal planning is rather efficient, but also where accessibility and socio-economy is rather different from other EU countries.

Figure 5 shows the result of the model of service sector plot ratio compared to the mapped plot ratio using the Danish national building register used in the heat atlas by Möller and Nielsen (2013).

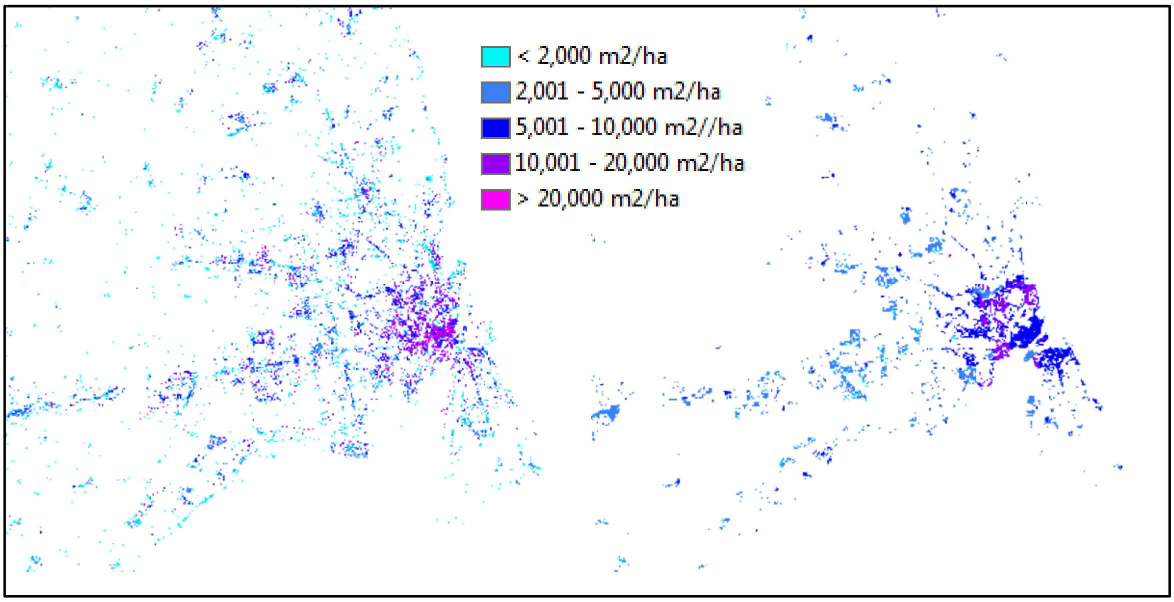

Figure 5: Comparison of registered plot ratio of service sector buildings (left) and modelled plot ratio (right) for Copenhagen, Denmark. The urban pattern is well represented by the model, although it may underestimate high-density areas, while increasing their area. Note that service sector buildings in rural areas are excluded because of the land cover mapping, which only includes urban areas.

Figure 6 shows an example of the cooling demand mapped at 100m resolution. The model suggests that cooling demand is much less coherently located than heat demand, which is because service sector buildings are confined to specific locations in urban and suburban centres as well as commercial zones. It has to be realized despite the high resolution that the model is not able to locate exactly where cooling demand is located within 1 km^2. Hence the cooling demand map will be aggregated to 1 km^2 resolution, while the cost-supply analysis uses the 100m resolution.

Finally, the large unknown is the difference between cooling demand and the actual rate of which it is met. The choice was therefore to only look at service sector buildings and to rather underestimate the cooling demand density.

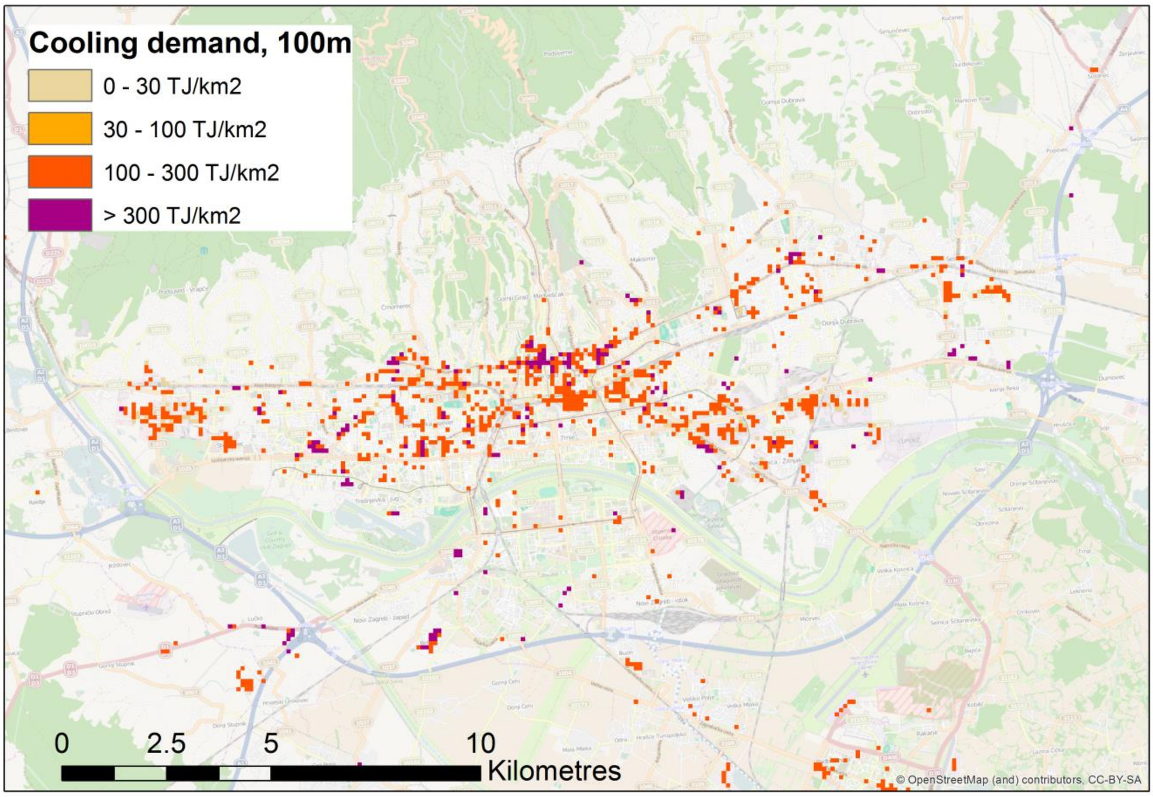

Figure 6: detail of the mapped cooling demand at 100m resolution for the city of Zagreb. Cooling demand is less coherent and confined to centres as well as service areas, it appears. It is not possible with the model to map exactly where cooling demand is located, but it gives a rather representative image of the distribution of urban cooling demand in the service sector.

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