Heat demand mapping and district heating assessment in data-pour areas

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Abstract
Buildings represent 40% of the European Union's energy consumption and 36% of its greenhouse gas emissions making it obvious that the decarbonisation of the European Union depends on the sustainable provision of heat in its cities. District heating presents it self as a clear solution to this issue. It is capable of supplying waste and renewable heat from where it is available to where it is needed and can provide a powerful driver for the integration of renewables in the electrical system through the flexibility that power to heat technologies can provide. Due to the inability of long-distance transport of heat, spatial planning and GIS mapping has proven to be a very important tool in heat planning. This usually requires a lot of highly detailed data which is often not available. The research presented in this paper is tackling this issue trough a heat demand mapping and district heating viability assessment method using mostly public databases. The developed method consists of three key steps: assessment of the aggregated heating demand, bottom up mapping used for validation and top down mapping of the entire observed area. The result of the mapping is used in the assessment of the district heating potential based on the difference between the price and levelized cost of heat as well as the assumed cost of the distribution infrastructure. The method has been implemented on the case of Croatia showing a significant potential for the economic utilisation of district heating.

Highlights:

- Heat mapping is an important tool for energy planning, but it is data intensive
- A flexible heat mapping and district heating assessment method has been developed
- Combination of aggregated assessment, bottom up and top down mapping
- Assessment based on the price of heat and the levelized cost of its production
- Validation of results and assessment of error based on bottom up mapping

Key words: Heat demand mapping; District heating; Energy Planning; GIS; Data-pour areas; Economic viability; Levelized cost of heat
Word count: 4751

Abbreviations

DH	District heating
EU	European Union
GIS	Geographic information system
LCOH	Levelized cost of heat

Nomenclature

Ag	Gross building footprint area [m2]
Cg	Average cost of grid per observed square [EUR]
FH	Floor height [m]
H	Building height [m]

HD	Heat demand [MWh/year]
HD	Heat demand [MWh/year]
HDS	Specific heat demand per building type [MWh/m2/year]
HP-LCOH	Difference between the average heat price and the levelized cost of heat [EUR/MWh]
NG	net to gross area ratio per building type [-]

1. Introduction and motivation

The European Union (EU) has set a very ambitious goal of a total or at least near-total decarbonisation until 2050 [1]. The majority of the overall emissions are attributed to the fuel combustion and fugitive emissions from fuels (without transport) with 2420 million tonnes of CO_2 equivalent or 54% in 2017 [2]. Buildings are the largest single energy consumer, 40%, and greenhouse gas emitter, 36%, across the EU [3]. According to the 2018 Revision of World Urbanization Prospects, 55% of the total World population is currently living in urban areas and this will most likely increase to 68% by 2050 [4]. As more and more people move into densely populated urban areas the sustainable provision of energy for space heating, cooling and production of domestic hot water will become an ever-increasing issue. Heating represents the largest demand both in terms of total annual and peak loads in 25 of the 28 EU countries among heating cooling and electricity demand, although that could change in the future due to ever increasing electrification [5]. Energy efficiency increases can help alleviate the issue, but it becomes uneconomical after a point and energy production from renewable sources becomes cheaper than further efficiency increases.

The options for a sustainable provision of energy in densely populated urban areas are quite limited. The use of fossil fuels in individual boilers is not compatible with the vision of a decarbonised Europe by 2050, individual biomass fired boilers will pose significant logistical problems related to the supply of fuel and management of ash alongside potential environmental issues linked to particulate emissions, individual resistive electric heating will be sensitive to increases in electricity prices and can have negative effects on peak electricity demand while individual heat pumps can face issues due to space constraints and price.

District heating (DH) presents itself as the only viable option due to its ability to utilize waste and renewable energy and transport high energy densities across large distances. Waste heat is an especially important factor since it is clean, cheap and abundant as shown in [6] for an example of 33 countries and [7] for northern China. Additionally, DH can enable the utilization of sources such as solar [8] and geothermal [9] energy as well as heat pumps [10] where they are available or feasible and transport the energy to where it is needed. Since it is essentially a distribution technology, DH provides great flexibility with regards to the use of energy source and transformation technology and enables the utilization of several energy vectors for the production. It is also a crucial component of future smart energy systems and a key driver for a higher level of integration of renewable energy sources since it can provide flexibility to the electrical grid if power to heat technologies are used [11][12][13]. DH is not always economically feasible due to its high initial investment costs so a detailed investigation is needed to determine if and in which areas it should be utilized. Its feasibility depends on three key factors:

1. Heat demand density;
2. Necessary supply temperature;
3. Availability of waste and renewable energy sources.

Spatial analysis can help tackle these questions and provide, depending on the scope of the investigation, an initial or a detailed assessment of the areas suitable for the utilization of DH. Geographic information system (GIS) based tools such as qGIS [14] and ArcGIS [15] enable such operations.

The results of these assessments rely heavily on the availability and quality of data, both aggregated and spatially distributed. This data is often not available or at least not public which can result in the inability to perform spatial assessments of energy demand or at least to validate the outcomes. For this reason, a three-step approach based mostly on publicly available data has been developed and implemented in this work, demonstrating a potential method for heat demand mapping and spatial assessment of the potential for the utilization of DH usable in data pour areas.

2. Heat mapping, district heating assessments and GIS utilization so far

Unlike electricity which can be transported long distances with relatively low losses, heat needs to be produced and consumed in a restricted geographic area. Liner heat and pressure losses represent technical while the cost of the needed infrastructure impose economic limitations for viable distances of heat distribution. Due to these reasons, spatial assessments of heat demand and supply are a crucial tool for heat and DH planning.

Several examples of the utilization of GIS for heat mapping and DH assessments can be found in literature. [16] for example presents a methodology utilizing land use and population density data alongside national averages for heating demand to produce a heat map for the city of Sheffield. The authors expect an error in the range of 20-25% based on the limitation of the utilized data. Similarly to that approach, the authors of [17] used national statistics for the US, divided into 11 census regions in order to calculate per capita heat demand and develop a heat atlas for the continental US. The calculation has taken average heating degree days for every state as well as land use and population density data. An assessment of the potential for the utilisation of DH has been conducted based on a minimum demand threshold. Degree day and highly detailed population data has been used to develop a top down heat demand map of Switzerland in [18]. On the other hand, the authors of [19] utilized detailed georeferenced building stock data including information on the type, use and age of buildings as well as the accounts of Danish energy producers to develop a heat atlas as well as an assessment of the potential for the utilization of DH in comparison to heat pumps. Utilizing even more data including the Danish Buildings and Dwellings registry, energy audits and detailed energy databases in [20], the authors have created a heat atlas with a resolution of a single building. When compared to measured consumption data the mean error ranged from 1% for industry and private sector service buildings, 15% for multi-story dwellings to 50% for public research and education buildings. The potential for the utilization of DH has been assessed using cost-supply curves. The same database has been used in [21] for the development of a heat atlas in one Danish municipality and assess the costs of energy savings measures. The authors of [22] utilized the atlas developed in [20] in order to assess the viability of using low temperature heat sources, such as low temperature industry excess heat, supermarkets, waste water, drinking and usage water, ground water, rivers, lakes and sea water in DH via heat pumps. The authors of [23] used similarly detailed data, including measured energy consumption, census and detailed building data to develop an energy atlas for a limited area including 3600 buildings. The authors of [24] used a multilinear regression model to dis-aggregate the cities energy consumption data to a single dwelling level based on building and household data for the city of Rotterdam for gas and electricity. Detailed bottom up heat demand assessment has been conducted using a 3D model of the city and building stock data. The results were then aggregated to comply with data privacy regulations. Multilinear regression has also been utilized in [25] to develop a top down heat demand map for 14 of the EUs largest countries. The model has been calibrated using Denmark as a reference due to its detailed building registry. A fixed minimum supply density of 20 TJ/km^2 has been used in order to assess the viability of DH utilization. The viability of the utilization of sewage heat in DH in Tokyo has been assessed in [26]. A bottom up method utilizing building polygons, heights and type has been used to generate the heat map while spatial correlations of demand and potential supply have been utilized to assess the feasibility.

GIS is often used in the spatial assessment of potential energy supply as well. Examples include assessments of wind [27], geothermal [28], solar [29], solar PV [30], wind and solar [31], tidal [32] biomass [33] and biogas from manure [34] as well as manure and agricultural waste [35]. It has also been used in assessing of specific sectors such as European museums in [36], neighbourhood level algae production [37] or hydrogen in road transport in [38] for example.

As shown in this chapter, various methods for GIS based heat mapping and GIS mapping in general exist. One common thread between all of them is the need for quality data. This makes the development of high-resolution heat maps and assessments of DH potentials in data-pour areas difficult. The method presented in this paper addresses this issue with a reliance on public and, in the case of the calibration, municipally owned data. The assessment of viability of DH is usually handled trough fixed minimum densities or trough the development of cost curves. The former gives a quick and broad overview of the available potential but does not take the impact of potentially cheep sources of heat into account while the latter relies on the availability of detailed technical and economic data. The method proposed in this research allows for a flexible result which determines the viability of DH implementation trough the minimum difference of price and levelized cost of heat (LCOH). This way, various heat sources can be considered through their LCOH, different economic conditions and business models' trough the prices of heat and the method is not heavily reliant on detailed data which is often not available.

3. Methods and tools

Due to the common lack of detailed data such as building censuses, existing energy demand and supply maps or public data used to create them, the proposed method utilized in this research relies on public databases as much as possible. Since this will inevitably require some assumptions, a three-step approach is proposed in order to calibrate and validate the results as well as assess the potential errors. These steps are:

1. Calculation of aggregate heat demand per defined region;
2. Bottom up demand mapping of one region;
3. Top down demand mapping of the entire observed area.

Once the maps are finalized, the potential for the utilization of district heating can be implemented.

3.1. Calculation of aggregate heat demand

The first step in the process is the definition of the highest level of aggregation for the calculation of the reference heat demand. In the case of this research, the level of individual municipalities has been selected. Following this selection, the heat demand of each municipality has been calculated based on the available data on the national and municipal level. The following data can be used for these calculations:

- Climate zone of the municipalities;
- Surface area of existing buildings per municipality or climate zone;
- Share of individual building types per municipality or climate zone;
- Specific heat demand per building category and climate zone;
- Population per climate zone;
- Population per municipality.

In this case, the total surface area of existing buildings in four categories, single family houses, multiapartment, private commercial and public buildings, have been collected as well as their shares based on construction period. Additionally, the specific heating demands per these categories were also gathered. Using these data, the total heat demand per climate zone has been calculated. Using the population data per climate zone, the specific per capita heat demand of each zone has been calculated and using that figure and the population of each individual municipality, the heat demand on a municipal level has been determined.

3.2. Bottom up mapping

Bottom up energy, in this case heat, demand mapping means that data is calculated with a very fine resolution and then aggregated to the final one. For the purpose of this research, the heat demand

has initially been calculated on the level of each individual building and then aggregated to a resolution of 1 ha (square of 100 m by 100 m).
The building level calculation is based on the following parameters:

- Building location and footprint area;
- Building height;
- Land use;
- Specific heat demand per building use category;
- Average floor height per building category;
- Net to gross surface area ratio per building category.

The heat demand is calculated using Equation 1.

$$HD = A_g \cdot NG \cdot (H/FH) \cdot HD_S \qquad \text{Equation 1}$$

HD – Heat demand [MWh/year]
A_g – Gross building footprint area [m^2]
NG – net to gross area ratio per building type [-]
H – Building height [m]
FH – Floor height [m]
HD_S – Specific heat demand per building type [$MWh/m^2/year$]
Once the heat demand is calculated it can be calibrated based on the municipal level data by modifying the floor height and net to gross surface area ratios per building category. Aside from the aggregate heat demand, the total heated surface area per building type can be compared and used for the calibration and validation of the results.

3.3. Top down mapping

Top down heat demand mapping is conducted by distributing the aggregate heat demand over a set area via georeferenced data. Depending on their availability, building census data, detailed population densities or building distribution databases can be used. Since detailed data on a national level are often not available, or not public, other sources can be utilised. This includes public pan-European or World-wide databases. Three main sources were utilized in this case:

- CORINE land cover maps [39];
- Population density map [40];
- Open street maps [41].

The CORINE land cover map provides information on the dominant type of land cover within the given grid. This includes both man-made structures and nature. Since only the first category is of interest, the CORINE map for the observed area was limited to layers representing buildings. Additionally, roads and areas covered by nature such as parks have been cut from the initial map to show a more realistic depiction of the actual situation. This map has then been intersected by a layer depicting the distribution of the municipalities and a 1ha grid. Finally, the data has been aggregated into the 1ha grid to obtain the areas per type of cover alongside the designation to which municipality each grid segment belongs. Weight factors are applied to each of the land cover types taken into account and the final aggregate cover area has been calculated.
A similar approach has been applied to the population density map. First, the specific population density per square meter has been calculated for each segment, the roads, bodies of water and natural coverage have been removed, and the resulting grid has been intersected with a vector layer representing the distribution of the municipalities and the grid of the selected resolution. Finally, the population density of each resulting square has been recalculated. The resulting map has then been corelated with the modified CORINE land cover map and a relation between the area and population has been determined. This needs to be done since the CORINE land cover map does not recognize sparsely built up areas resulting in a significant error.

The combination of the modified CORINE land cover and population density maps has been used to distribute the calculated heat demand on a municipal level (described in chapter 3.1). This finally results in a heat demand map of the entire observed area with a resolution of 1 ha (square of 100 by 100 meters). These results can be compared with a bottom up map or similar reference data and calibrated accordingly. This process has been implemented in this case. The bottom up and top down data have been compared and the weight factors have been modified in order to minimize the difference.

3.4. Assessment of the potential for the utilization of district heating

In order to assess the potential for the utilization of district heating regardless of the heat supply technology, an assessment based on the difference of the average heat price and LCOH has been developed and implemented. The potential is calculated using Equation 2

$$(HP - LCOH) \cdot HD - C_g = 0 \qquad \text{Equation 2}$$

(HP-LCOH) – Difference between the average heat price and the levelized cost of heat [EUR/MWh]
C_g – Average cost of grid per observed square [EUR]
HD – Heat demand [MWh/year]
The HP-LCOH value is determined for each observed grid segment for which the result of the above presented equation equals 0. This provides the minimum difference between the average price at which the heat is sold at and the levelized cost of its production for which the implementation of district heating is economically justified. The grid cost, C_g represents the annual cost of the grid's installation (annual depreciation with a time frame of either it's lifetime or the project funding duration) and its operation and maintenance. This way, it can be assumed that no grid exists. Since the specific grid cost depends greatly on the type of terrain, heat demand and available as well as necessary routs the grid can or must take, it is difficult or in some cases impossible to determine an accurate figure. For this purpose, several cost levels can be chosen, and results can be presented for each demonstrating the sensitivity of the assessments as well as presenting different results for different segments of the assessed areas. In cases where a specific cost can be determined with a high degree of accuracy, it can and should be used.

4. Implementation

The above-mentioned method has been applied on Croatia (aggregate heat demand calculation and top-down mapping) and the City of Zagreb (bottom up mapping). The City of Zagreb has been selected for the second step of the method for two reasons: it holds close to 20% of the total population of Croatia as well as roughly 23% of the total heat demand and the necessary data for the implementation of the step have been made available.
The aggregate heat demand of each municipality has been calculated based upon the Croatian census, official climate zone classification and the Long term strategy for the refurbishment of the building sector of Croatia [42]. Using these data sources and the method described in chapter 3.1. This resulted in the distribution of surface area per building type and climate zone as well as the aggregate heat demand per climate zone. Using this and the information on the population per climate zone and for each municipality, the aggregate heat demand for each one was determined.
The bottom up map has been created using the cities cadastre, land use maps and LIDAR recordings, all provided by the Office for Spatial Planning of the City of Zagreb, City Office for the Strategic Planning and Development of the City of Zagreb, City Office for Cadastre and Geodetic activities of the City of Zagreb as well as the City of Zagreb itself. The cadastre maps were used to define the location and footprint areas of each building, the land use map data was added to this this dataset to determine the use of each building and finally, the LIDAR was used to calculate each buildings height. Table 1 shows the assumptions used in the bottom up mapping of the City of Zagreb.

Table 1 Assumptions used in the bottom up mapping of the City of Zagreb

Building type	Floor height (FH) [m]	Net to gross ratio (NG)
Residential	3	0.75
Commercial	3.3	0.7
Public	2.8	0.7

Table 2 presents the specific heat demands used in the bottom up mapping of the City of Zagreb per building type. Unfortunately, no information on the age of the buildings or their condition is available so such data could not have been used in this case. Table 3 presents an additional modification of the specific heat demand based on the use type of the individual buildings. This modification is introduced to accommodate inclusion of buildings which are under construction, in occasional use or not in use, for example ruins.

Table 2 Specific heat demand per building category [43]

Building category	Specific heat demand [kWh/m^2]
Residential	179
Commercial	170
Public	170
Mixed	179
Agricultural	100
Special	170
Transport	170
Education	169
Sport and recreation (buildings only)	170
Market and trade	170
Hospitality and tourism	170
Religious	170
Healthcare	292

Table 3 Modification of specific heat demand

Special building category	Heat demand modification
Residential use	1
Commercial building	1
Auxiliary building	0.8
Buildings under construction	0
Sports and recreation	1
Public buildings	1
Ruin	0
Buildings for occasional use	0.7

The aggregated surface areas calculated on the level of each municipality and the values presented in Table 1 were used to calibrate the resulting map and with that the total aggregate heat demand of the City of Zagreb. Table 4 presents the results of this calibration. The reference building shares of the residential, commercial and public categories for urban areas in Croatia as well as the calculated data obtained from the bottom up mapping of Zagreb can be seen.

Table 4 Reference aggregate and calculated bottom up data for the city of Zagreb

	Residential	Commercial	Public
Reference data [42]	67,14%	23,85%	9,01%
Bottom up mapping	67,06%	23,77%	9,17%

Data presented in Table 3 were used to calibrate the total aggregated heat demand alongside the data in Table 1. The difference in the bottom up and reference heat demands for the city of Zagreb is 0,6%

In order to move onto the top down calculation, the data sets used for the spatial distributions of the aggregate values need to be prepared. Figure 1 presents the spatial distribution of roads [41], bodies of water [39] and natural areas [39,41] used to modify the population distribution [40] and the CORINE land cover maps [39].

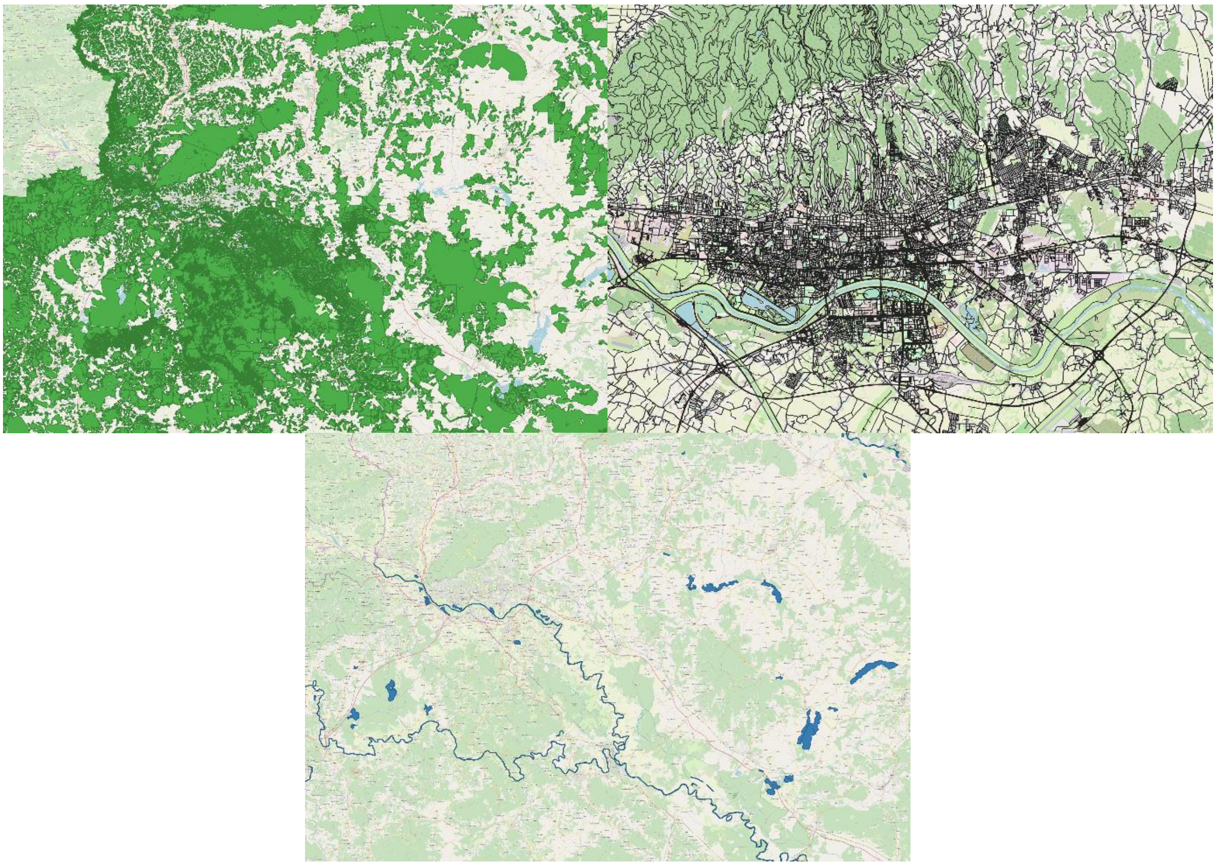

Figure 1 Spatial distribution of roads, bodies of water and natural areas

Figure 2 and Figure 3 present the result of the modification of the CORINE land cover and population density maps with the above presented data sets. As it can be seen, the resulting maps have a much more varied distribution and a more realistic representation of the real-Word situation. These modified maps and the determined weight factors have been used to distribute the aggregate heat demand of each municipality on a 1 ha grid. The weight factors were obtained through an iterative process where the absolute sum of all differences between the top down and bottom up heat demand maps was minimised using Equation 1.

$$\sum_{n=1}^{n=X} |HD_{nTD} - HD_{nBU}| = min \qquad \text{Equation 3}$$

n – number of compared cells [-]

HD_{nTD} – heat demand of cell n calculated using the top down method [MWh]
HD_{nBU} – heat demand of cell n calculated using the bottom up method [MWh]

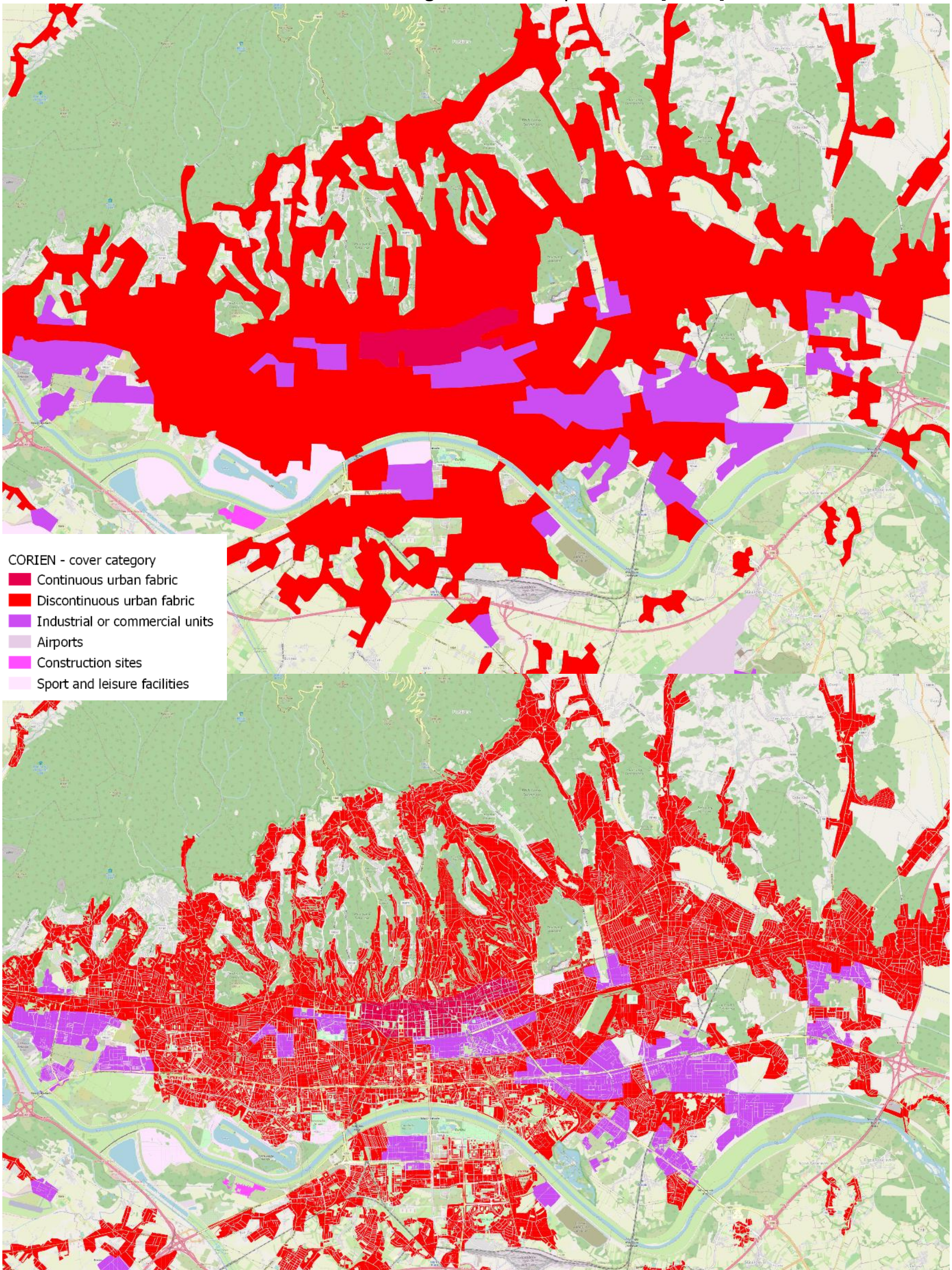

Figure 2 CORINE land cover map; original data (up) and modified data (down)

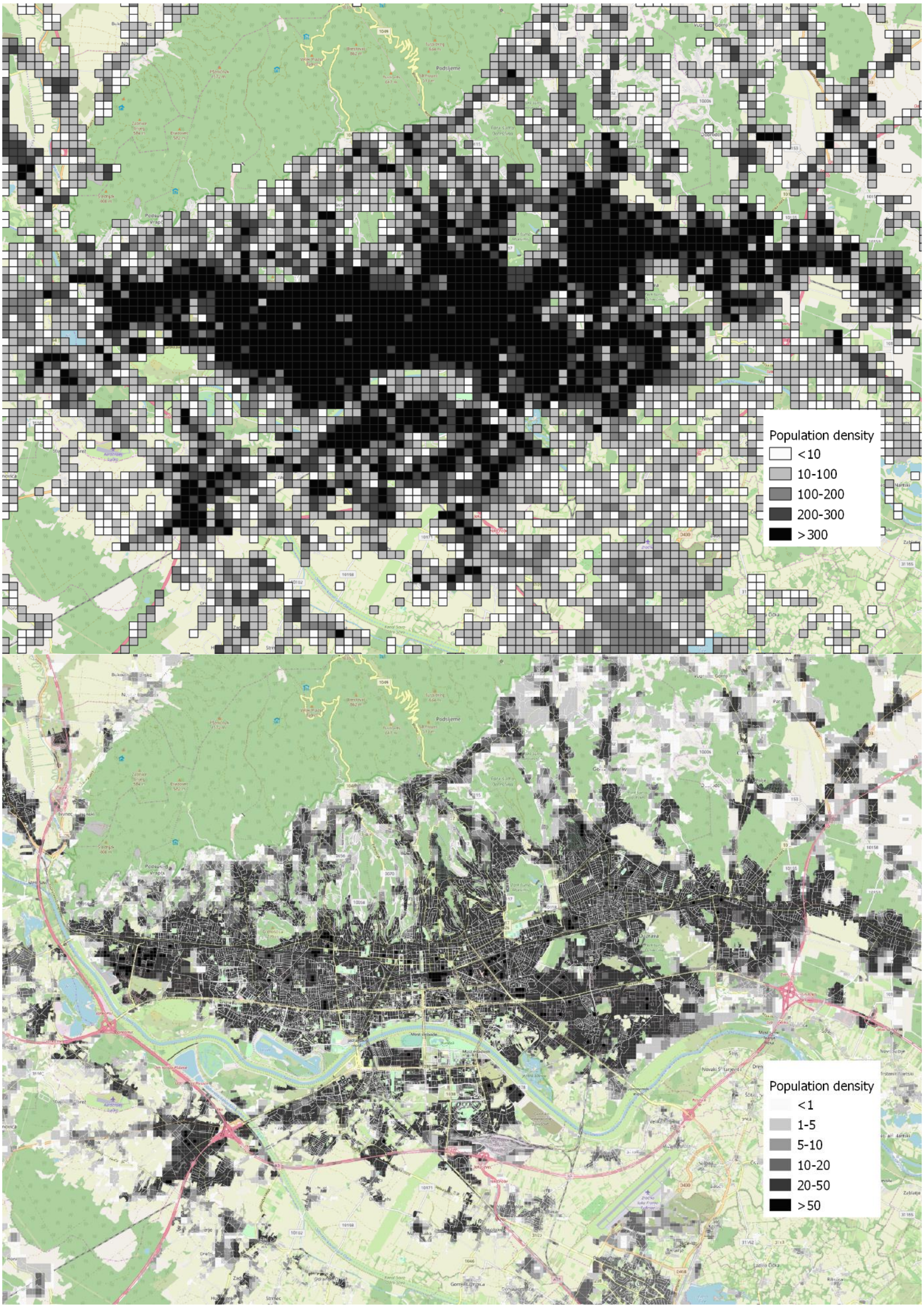

Figure 3 population density map; original data (up) and modified data (down)

The final weight factors can be seen in Table 5. The results of this process are presented in chapter 5.

Table 5 Final weight factors used for spatial distribution

CORINE code	Land cover type	Final weight factor
111	Continuous urban fabric	3,11
112	Discontinuous urban fabric	0,37
121	Industrial or commercial units	0,26
133	Construction sites	0,25
142	Sport and leisure areas	0,16

5. Results

Figure 4 presents an example of the results of the top down mapping of Croatia's heat demand with a resolution of 1 ha.

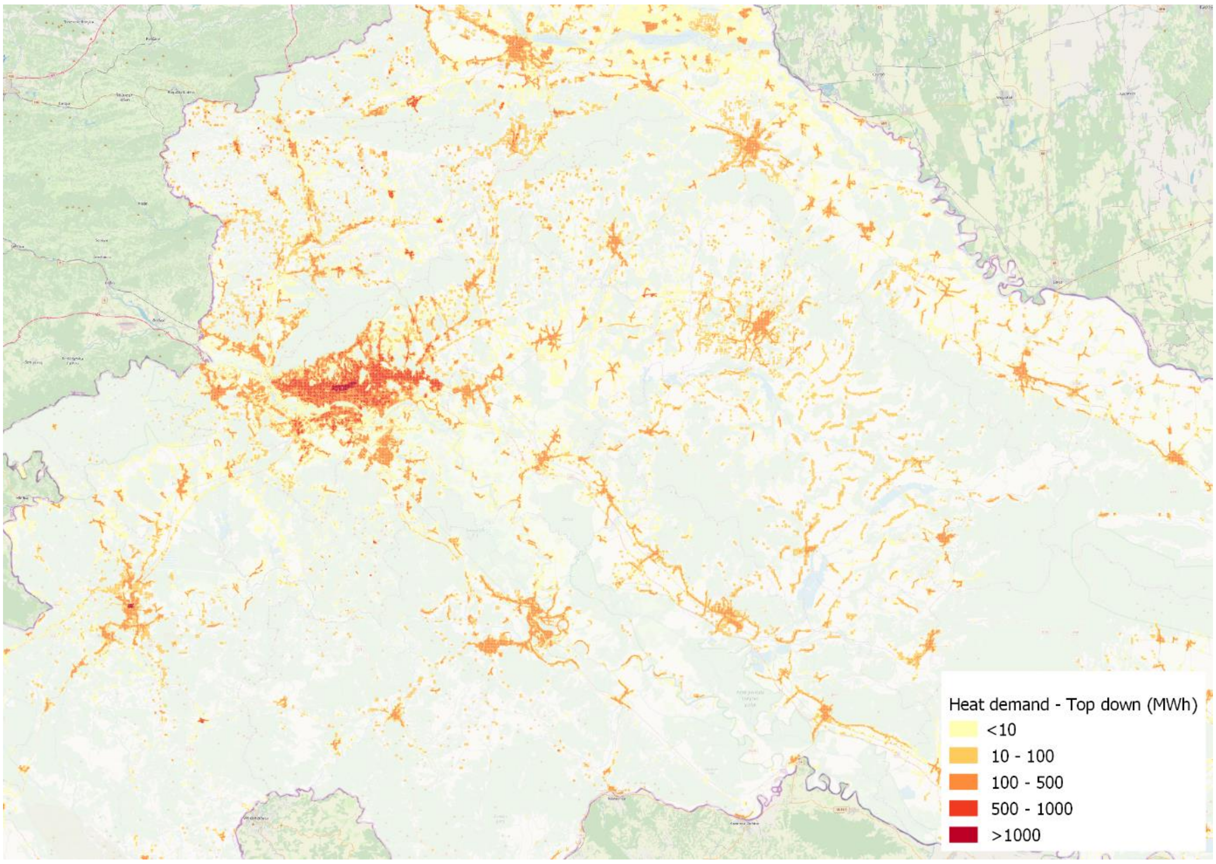

Figure 4 Top down heat demand

Figure 5 shows the comparison of the bottom up (above) and top down (below) heat demand mapping for the city of Zagreb. As the figure shows, the heat demand matches up visually for the two cases. It can be observed that the bottom up map has larger densities of demand distributed over a smaller area when compared with the top down map. This is expected since the bottom up mapping utilizes the actual distribution of built up areas based on individual buildings whereas the top down one relies on the distribution based on a fixed resolution. The removal of roads, bodies of water and natural areas does bring these distributions closer to one another, but some differences do persist. It is important to note that the total sum of both heat demands is the same.

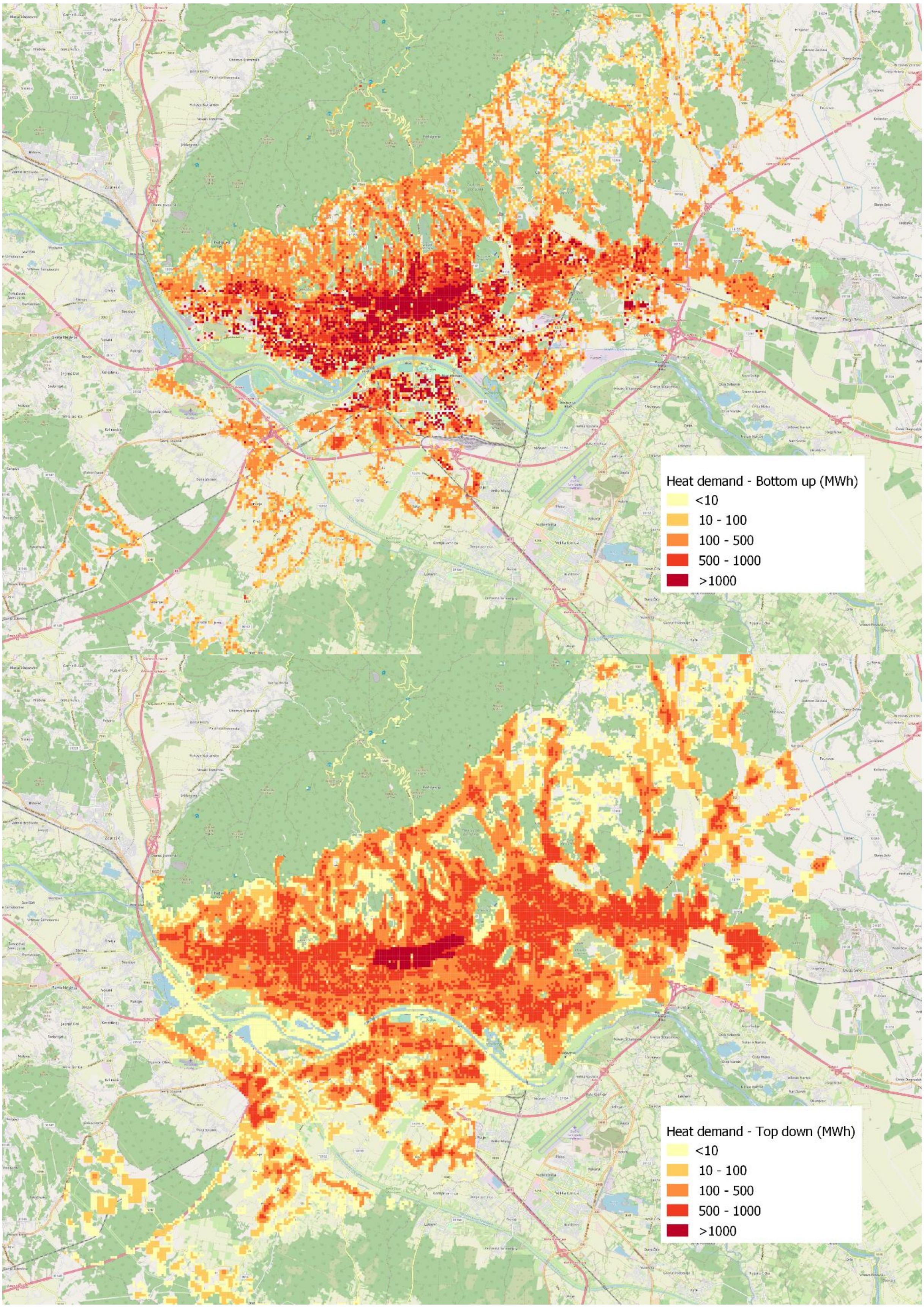

Figure 5 Bottom up (up) and top down (down) heat demand

The quantified differences between the two maps can be observed in Figure 6. It presents the heat demand (Y axis) of both maps for each 1 ha square based on their location (X axis). It is important to note here that the peak demand of both cases matches up both with regards to its location and magnitude. The peak demand of the bottom up map is 257.814 MWh, and 259.732 MWh for the top down one. This is a difference of 0,74%. The figure also represents the overall differences in peeks and spread of both maps where the bottom up one has higher peeks but a smaller spread then the top down one. This results in a relatively flatter curve for the top down map.

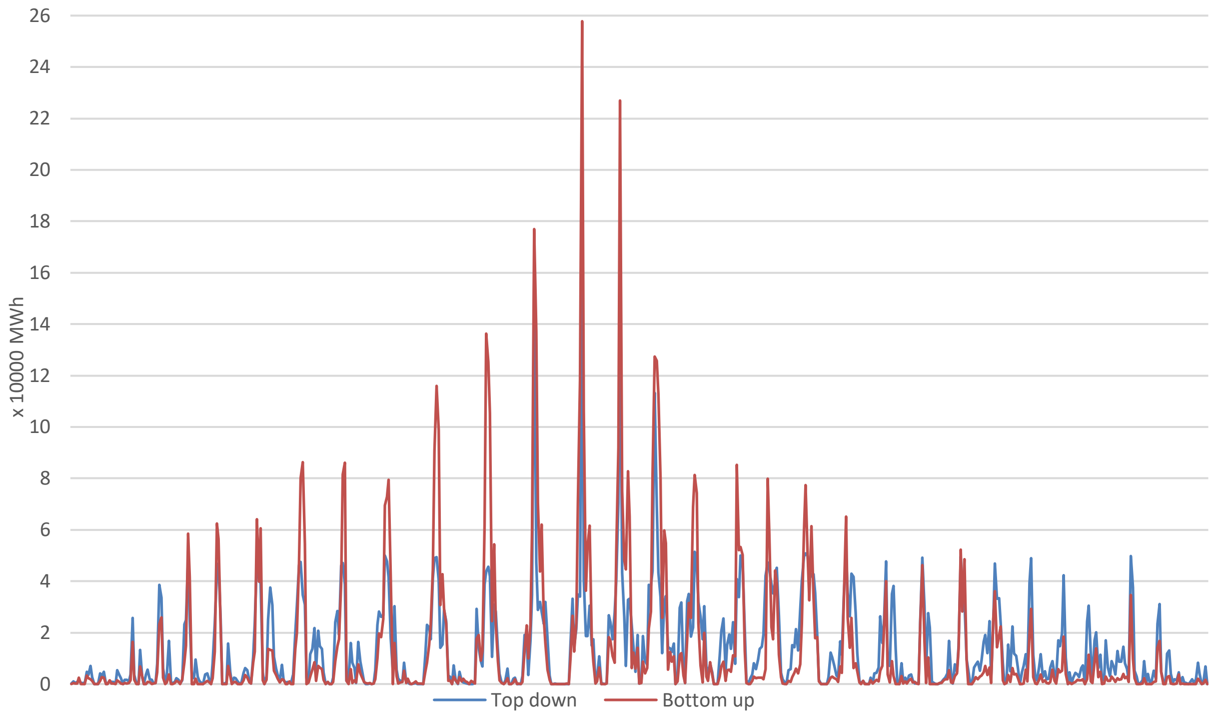

Figure 6 Distribution of top down and bottom up heat demand

Figure 7 shows the distribution curve for both maps in the format of a load duration curve. It can again be observed that the peak demand in both cases matches up and that the overall peeks of the bottom up map are higher on average.

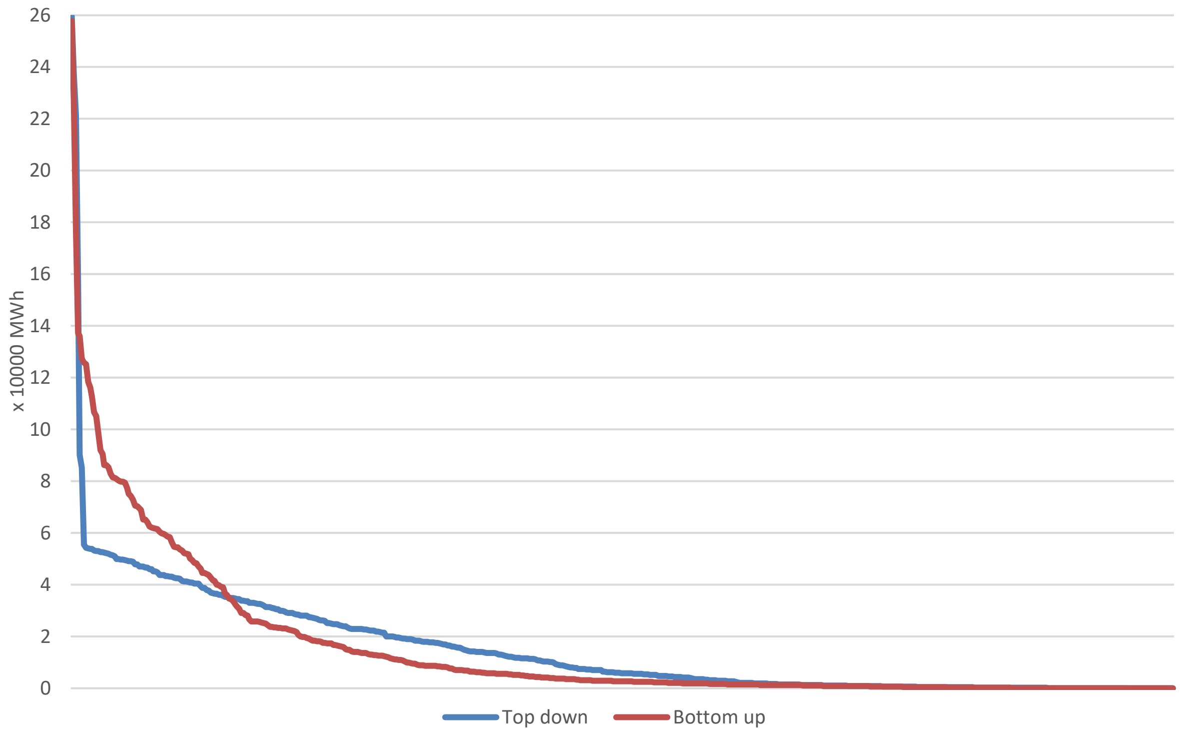

Figure 7 Distribution curve of top down and bottom up heat demand

Figure 8, Figure 9 and Figure 10 present the results of the DH potential analysis for three selected annual grid costs (5.000, 10.000 and 15.000 EUR/ha) at a resolution of 1 ha for the cities of Zagreb (left) and Rijeka (right). It can be observed that the assumed grid costs do have a significant impact on the end results, as was expected.

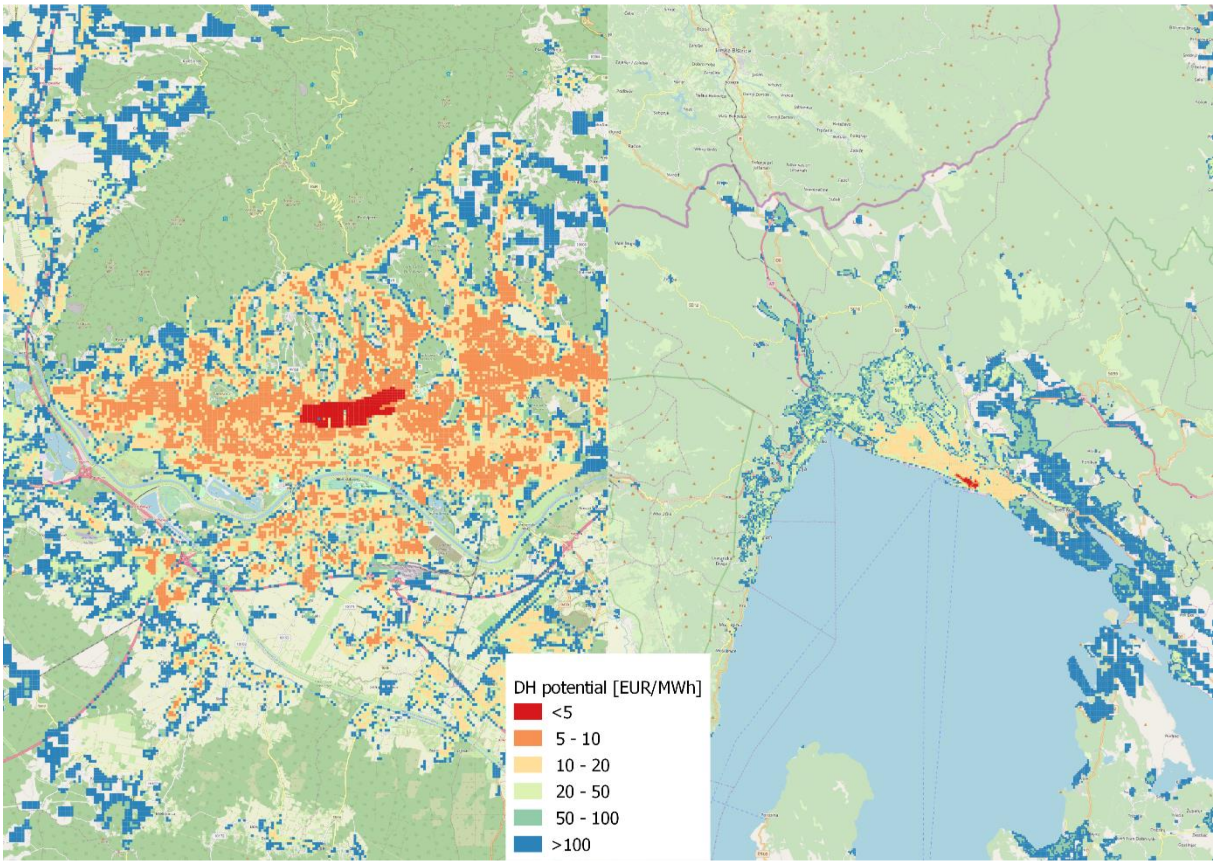

Figure 8 District heating potential with grid cost of 5.000 EUR/ha

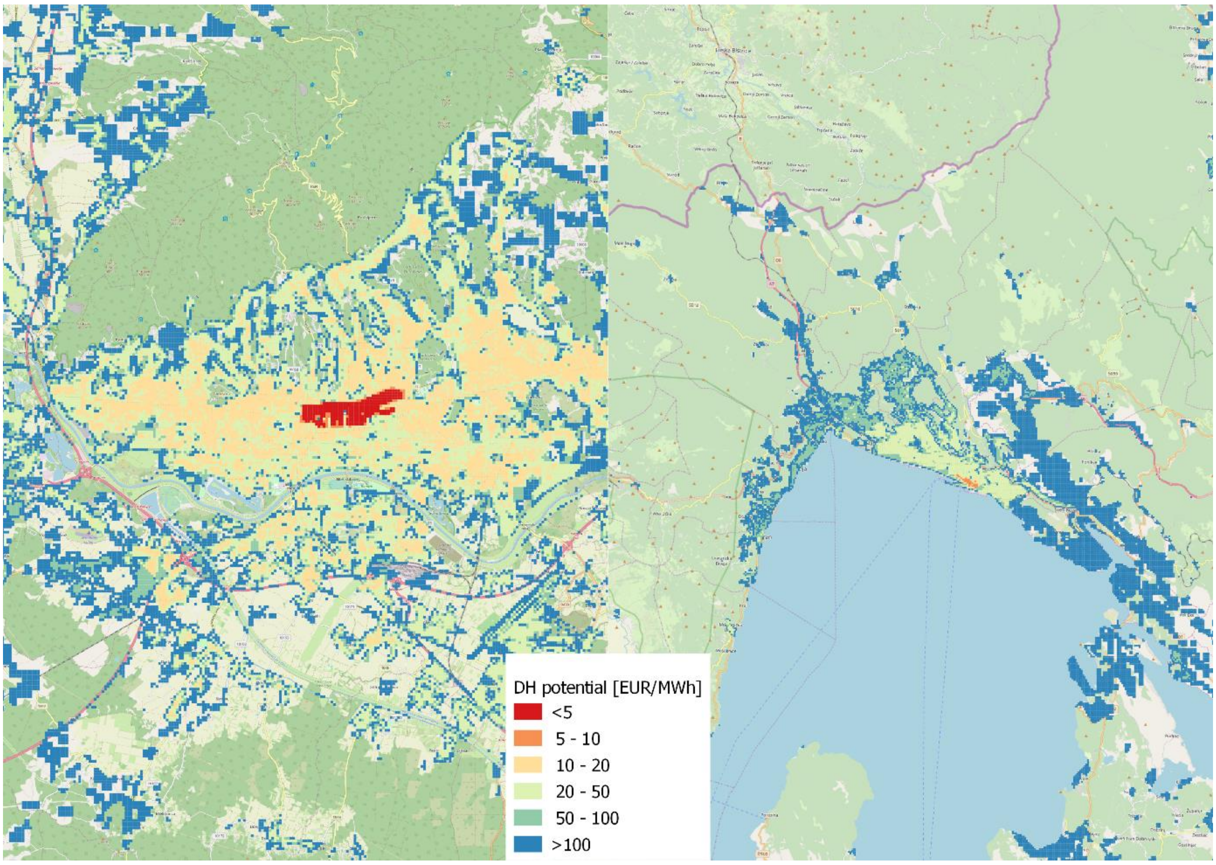

Figure 9 District heating potential with grid cost of 10.000 EUR/ha

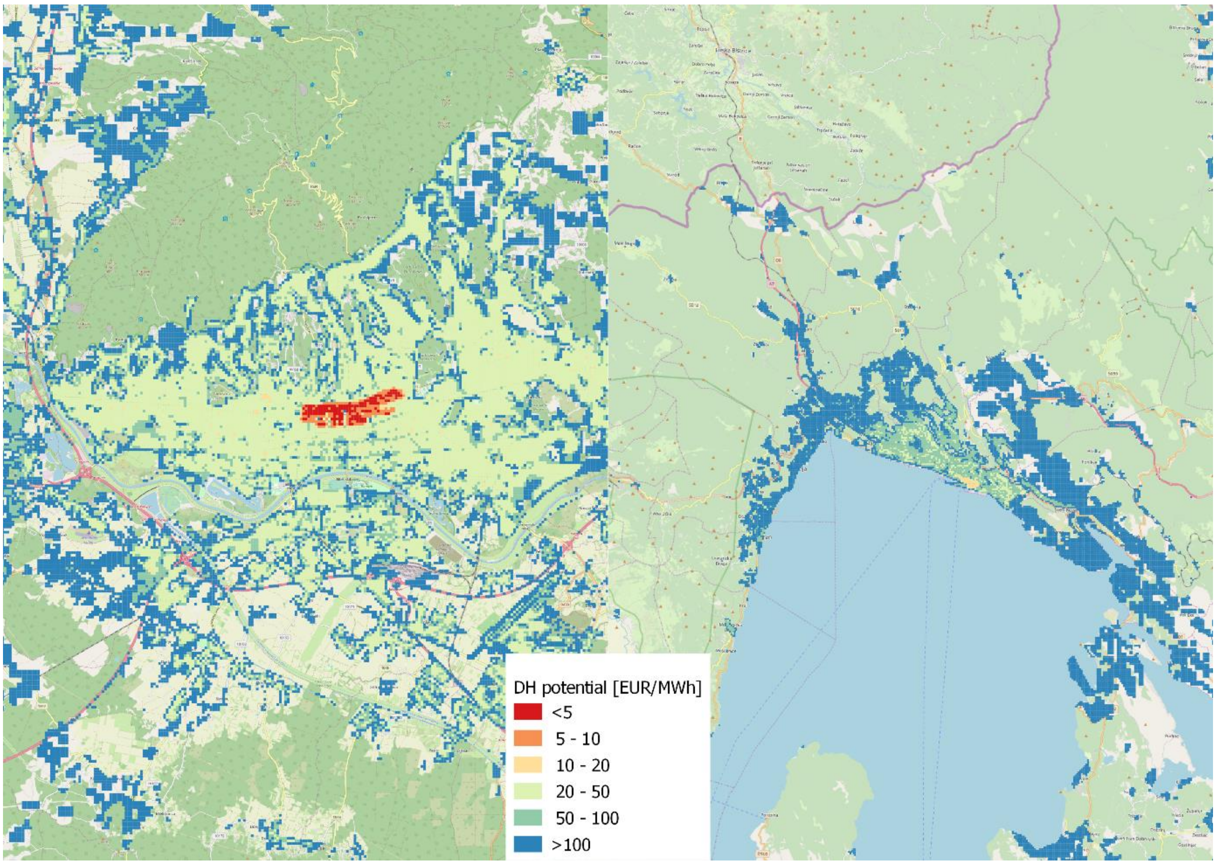

Figure 10 District heating potential with grid cost of 15.000 EUR/ha

Table 4 shows the comparison of the DH potential analysis for the bottom up and top down heat demand mapping for the City of Zagreb with the three different grid costs. The values in the table present which percentage of the heat demand falls below the HP-LCOH price level. This for example means that in the case of the 5.000 EUR/ha grid cost, 88% of the heat demand of the city can be economically covered trough DH if the average price of heat is 20 EUR/MWh above the LCOH for the bottom up mapping method. The same result would be 90% in the case of top down mapping. In case of the 10.000 EUR/ha grid cost and the same heat price level, the results are75% for the bottom up and 55% for the top down mapping method. The table also shows a consistent underestimation of the potential for the top down mapping when compared with bottom up at lower prices. This is to be expected because of the lower peeks of heat demand in the top down maps when compared to bottom up ones, as seen in Figure 6 and Figure 7. These differences are smaller for lower grid costs and larger for the higher ones. It can therefore be concluded that the results of the top down mapping can be considered as conservative.

Table 6 District heating potential for the City of Zagreb at a resolution of 100X100m

	5 kEUR		10 kEUR		15 kEUR	
Price EUR	Bottom up	Top Down	Bottom up	Top Down	Bottom up	Top Down
<5	52%	11%	30%	10%	16%	6%
<10	74%	55%	52%	11%	40%	11%
<15	84%	84%	66%	13%	52%	11%
<20	88%	90%	74%	55%	62%	12%
<25	91%	93%	80%	77%	69%	24%
<30	93%	95%	84%	84%	74%	55%

<35	94%	95%	86%	88%	78%	72%
<40	95%	96%	88%	90%	81%	80%
<45	96%	96%	90%	92%	84%	84%
<50	97%	96%	91%	93%	86%	86%
<55	97%	97%	92%	94%	87%	89%
<60	97%	97%	93%	95%	88%	90%
<65	98%	98%	94%	95%	90%	91%
<70	98%	98%	94%	95%	90%	92%
<75	98%	98%	95%	95%	91%	93%
<80	98%	98%	95%	96%	92%	94%
<85	98%	98%	96%	96%	93%	95%
<90	99%	98%	96%	96%	93%	95%
<95	99%	98%	96%	96%	94%	95%
<100	99%	98%	97%	96%	94%	95%

Table 7 shows the same results as Table 6 but for a resolution of 100 ha.

Table 7 District heating potential for the City of Zagreb at a resolution of 1.000X1.000m

	400 kEUR		800 kEUR		1.200 kEUR	
Price EUR	Bottom up	Top Down	Bottom up	Top Down	Bottom up	Top Down
<5	34%	13%	8%	9%	3%	3%
<10	67%	45%	34%	13%	16%	11%
<15	74%	68%	58%	16%	34%	13%
<20	81%	78%	67%	45%	51%	13%
<25	86%	85%	72%	59%	62%	28%
<30	88%	89%	74%	68%	67%	45%
<35	90%	91%	79%	74%	71%	54%
<40	90%	93%	81%	78%	72%	62%
<45	91%	93%	83%	83%	74%	68%
<50	93%	93%	86%	85%	77%	72%
<55	93%	94%	86%	86%	80%	77%
<60	93%	95%	88%	89%	81%	78%
<65	94%	95%	89%	89%	83%	81%
<70	94%	96%	90%	91%	85%	84%
<75	95%	96%	90%	92%	86%	85%
<80	95%	97%	90%	93%	86%	86%
<85	95%	97%	91%	93%	87%	87%
<90	96%	97%	91%	93%	88%	89%
<95	96%	97%	92%	93%	89%	89%
<100	96%	98%	93%	93%	89%	90%

Table 8 presents the results of the DH potential assessment based on the top down heat demand map of Croatia on a 1 ha raster. It can for example be observed that at a PH-LCOH (Price EUR in the table) level of 30 EUR/MWh, 61% of the total heat could be economically supplied trough DH if the network cost is 5.000 EUR/ha annually on average. This level drops to 31% and 16% for grid costs of 10.000 and 15.000 EUR/ha.

Table 8 District heating potential for Croatia at a resolution of 100X100m

Price EUR	5 kEUR	10 kEUR	15 kEUR
<5	3%	2%	1%
<10	16%	3%	3%
<15	31%	4%	3%
<20	44%	16%	4%
<25	54%	25%	7%
<30	61%	31%	16%
<35	67%	38%	22%
<40	71%	44%	27%
<45	75%	49%	31%
<50	77%	54%	36%
<55	79%	58%	40%
<60	81%	61%	44%
<65	82%	64%	48%
<70	84%	67%	51%
<75	84%	69%	54%
<80	85%	71%	57%
<85	86%	73%	59%
<90	87%	75%	61%
<95	87%	76%	63%
<100	88%	77%	65%

6. Discussion

The results presented in Table 8 demonstrate a significant potential for the economic utilization of DH in Croatia. Depending on the assumed grid cost, this ranges from 77% to 36% at a heat price of 50 EUR/MWh above the LCOH. The range of results also points at a very strong impact of the network costs on the overall economic feasibility of DH systems. The results of the study demonstrate a high potential for the economically feasible utilization of DH in the case of both Croatia and the City of Zagreb. The methodology presented in this research allows for a lot of flexibility both from the perspective of grid costs and supply options. By creating maps with different grid costs, it is possible to identify priority areas and "hotspots" of DH potential with a variety of criteria. Densely built up urban areas can, for example, be assessed utilizing a higher grid cost assumption then a more sparsely built up one due to the higher costs of construction (need to dig below built up areas) and a need for more pipes per hectare (due to a larger number of users per ha). On the other hand, by assuming a heat price and identifying potential technologies for its supply in a given area, a price level can be selected as a reference point. For example, if a price of heat of 70 EUR per MWh is assumed and a source with a LCOH of 20 EUR/MWh is available, a price level of 50 EUR can be taken as a reference for the assessment of the potential of DH supply. Taking both variations into account allows for the flexibility needed for such assessments to be made in areas lacking high quantities of quality public data.

The validation of the heat demand mapping presented in Figure 5, Figure 6 and Figure 7 as well as Table 6 and Table 7 point towards the same conclusion. The top down mapping demonstrated in this research will result in lower average peeks but a wider average spread of the heat demand when compared with bottom up mapping. This is especially visible in Figure 6 where a comparison of both mapping methods is shown. The figure presents both heat demands for each 1 ha area. This difference is to be expected since bottom up mapping uses less uniform data of a higher resolution, individual buildings compared to a limited number of cover types or population levels. The impact of these differences on the result of the assessment of the viability of DH depends greatly on the assumed costs of the DH grid. It can be seen that the potential is consistently lower in the case where the top down map is utilized. The impacts are strongest at low price levels and at high assumed grid costs. This strongly points to the conclusion that the results of the top down mapping can be taken as conservative.

The demonstrated mapping and assessment method relies mostly on public data in the form of national aggregated energy statistics and public georeferenced databases, while limiting the use of more detailed data which is often only available for a very limited are for the validation and calibration steps. This approach allows data pour areas to develop high resolution and high quality heat demand maps and DH assessments with the limited data available to them.

7. Conclusion and future work

The research in this paper presents a method for heat mapping and the spatial assessment of the viability of DH in data-pour areas. It relies mostly on publicly available and, for the purpose of calibration and validation, municipally owned data. The method consists of the following three steps:

1. Calculation of aggregate heat demand per defined region;
2. Bottom up demand mapping of one region;
3. Top down demand mapping of the entire observed area.

The spatial assessment of the viability of district heating utilizes the difference between the average heat price and the levelized cost of heat instead of a fixed minimal density or cost curves to both provide a flexible set of results and be usable in cases where detailed economic and technical data is not available. This results in a flexible method which allows for a varied assessment of different areas considering a wide variety of potential heat sources and technologies.

The heat demand mapping and assessment of district heating viability has been implemented on the case of Croatia (steps 1 and 3) with the City of Zagreb used for the validation and calibration of the top down mapping step (step 2). The results of the validation show an expected deviation between the results of the bottom up and top down mapping due to the difference in peaks in heat demand which are the result of the higher resolution of the data used in the bottom up mapping. These deviations impact the assessments of the viability of district heating as well, with a stronger impact in cases where a higher grid costs is assumed.

The overall method provides a flexible tool for the assessment of the viability of district heating systems in data pour areas, regardless of the utilized heat sources. The final results of this method do demonstrate a consistent underestimate of the DH potential due to the uniformity of the publicly available spatial data if compared to a detailed bottom up assessment, however these discrepancies are mostly present in the cases where the assumed heat price is only marginally higher then the LCOH. The future wok related to this research will focus on the spatial assessment of cooling demand and district cooling potential.

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