Sustainable cooling supply of cities and urban areas – Spatial assessment of cooling demand and district cooling potential using public data

Abstract

Europe's building sector represents its largest single energy consumers and greenhouse gas emitters. Although space heating and the preparation of domestic hot water are responsible for the largest share of their energy demand, cooling is becoming an important factor with the rise of the global temperatures and the increased living standards across the continent. The decarbonisation of the cooling sector is a challenge especially relevant in densely populated urban areas and as with heating, district cooling is proving to be an effective solution for the supply of the needed energy densities in these conditions. However, unlike district heating, the assessment of the potential for the utilization of district cooling is not well addressed and researched. The research in this paper proposes a flexible method for the assessment of the spatial distribution of cooling demand and the assessment of the viability for the utilization of district cooling using mostly public data combining a bottom-up and top-down mapping approach. The method has been implemented on the case study of Croatia (top-down) and the City of Zagreb (bottom-up) and it demonstrated a high potential for the utilization of district cooling in both cases.

Keywords: Cooling demand mapping; District cooling; Energy Planning; GIS; Levelized cost of cooling; Urban cooling

Funding: This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

1. Introduction

The European Union (EU) is setting ever more ambitious energy and climate goals with the ultimate target of a total or at least near total decarbonisation by 2050 (EUROPEAN COMMISSION, 2018). With 55% of the World's population currently living in urban areas and a trend of this figure increasing to 68% by 2050 (United Nations, 2018), it is evident that the sustainable supply of energy in cities and other densely populated areas is a priority. This point is additionally supported by the fact that buildings are the largest single energy consumers and greenhouse gas emitter responsible for 40% of the primary energy demand and 36% of all emissions across the EU (European Commission, 2019). Power and heat supply are mostly at the centre of this discussion, however with the impact of global warming and climate change as well as the increased purchasing power and higher living standards across Europe the supply of energy for cooling is becoming more important. This is highlighted in the European Environment Agency research (European Environment Agency, n.d.) which shows that the average population-weighted cooling degree days are steadily increasing. The linear trend from 1981 until 2017 shows an increase from 73,7 to 107,2 cooling degree days. The linear trend of the average population-weighted heating degree days has declined in the same period from a value of 2.314,4 to 2.082 heating degree days.

The importance of district heating as an option for the sustainable supply of heat and the utilization of various renewable energy sources such as geothermal (Huculak, Jarczewski, & Dej, 2015) and solar (Huang, Fan, & Furbo, 2019) as well as waste heat (Oró, Taddeo, & Salom, 2019) is very well researched as is its potential to act as mechanism to link the power and heating sectors (Lund, Duic, Østergaard, & Mathiesen, 2018). This is also true for the use of Geographic information system (GIS) based tools such as qGIS ("QGIS project!," n.d.) and ArcGIS ("ArcGIS," n.d.) in the assessments of their potential and viability (Novosel, Pukšec, Dulić, & Domac, 2020), (Meha, Thakur, Novosel, Pukšec, & Duić, 2021). Outside of the heating sector, GIS tools are also often used in a variety of other energy related fields such as the assessment of wind (Jangid et al., 2016), geothermal (Viesi, Galgaro, Visintainer, & Crema, 2018), solar, (Groppi, de Santoli, Cumo, & Astiaso Garcia, 2018) and biomass (Zyadin et al., 2018) for example. It has also been used in the assessment of specific sectors relevant to cities and urban areas such as the prediction of urban heat islands (Equere, Mirzaei, Riffat, & Wang, 2021), energy demand of cultural buildings (van Schijndel & Schellen, 2018), algae production (Dutt et al., 2017) and the viability of hydrogen for road transport (Rahmouni, Settou, Negrou, & Gouareh, 2016). On the other hand, the spatial assessment of cooling demand and the viability of district cooling is still under-explored. Some research into the topic does exist, for example the Pan-European Thermal Atlas developed under the Heatroadmap Europe project, does include cooling demand assessments (Möller et al., 2019), (Connolly, 2017), however the focus is firmly placed on the aspect of heat supply and demand. The authors of (Pampuri, Cereghetti, Strepparava, & Caputo, 2016) have proposed a method to use electricity consumption data to assess actual cooling needs with high accuracy while the authors of (Yi & Peng, 2017) have corelated cooling demand with local climate data and real estate prices for the case of Seoul. Both methods require detailed data which is often not available, such as remote metering data in the case of the former and microclimate data in the case of the later work. The lack of research into the use of district cooling when compared to heating is likely linked to its lower rate of utilisation.

Most of the benefits and the limitations of district heating are valid for district cooling as well. It enables the utilization of otherwise unusable cooling sources such as free and waste cooling (Fahlén, Trygg, & Ahlgren, 2012), (Hsu, Lin, Liang, Lai, & Chen, 2019), as well as the diversification of supply options (Thakar, Patel, & Patel, 2021). As with heating, district cooling is most suited for high-density urban areas (Shi, Hsieh, Fonseca, & Schlueter, 2020), (Shi, Fonseca, & Schlueter, 2021) where it can lead to significant efficiency gains (Alajmi & Zedan, 2020). District cooling provides the potential to supply renewable cooling at higher energy densities, lower costs and with lower land use, compared to individual systems thus making them a vital component in the decarbonisation of the building sector and the overall sustainability of the energy supply in densely populated urban areas. The high investment costs in such systems as well as the reliance of its economic feasibility on the spatial conditions and the location of the potential supply and demand make GIS based tools ideal for the assessment of its potential. The quality of these assessments is reliant on the quality and availability of data which is often not accessible.

The focus of this research is the development and demonstration of a flexible method of cooling demand mapping and the assessment of district cooling potential which focuses on the use of public data. The proposed method is capable of mapping and assessing large areas such as regions and countries. The method has been implemented and validated on the cases of the City of Zagreb and the Republic of Croatia.

2. Methodology – Theory

Spatial assessments commonly rely on large quantities of data, both georeferenced and not. Assessments of spatial energy demand often utilise detailed building censuses which incorporate data such as gross and/or net areas, use categories, age and energy categories based on a certification system. As such data is often not available, or is at least not public, certain approximations need to be utilized. The method proposed in this research relies mostly on publicly available data and data available to cities and municipalities. It consists of the following 4 steps:

1. Calculation of the speciffic cooling demand for the selected building types;
2. Bottom-up cooling demand mapping for the reference location;
3. Top-down cooling demand mapping and calibration via the reference location;
4. Assessment of the district cooling potential.

Figure 1 presents a graphical representation of the proposed method for the development of the bottom-up and top-down cooling demand maps. The method is described in depth in chapters 2.1 to 2.4.

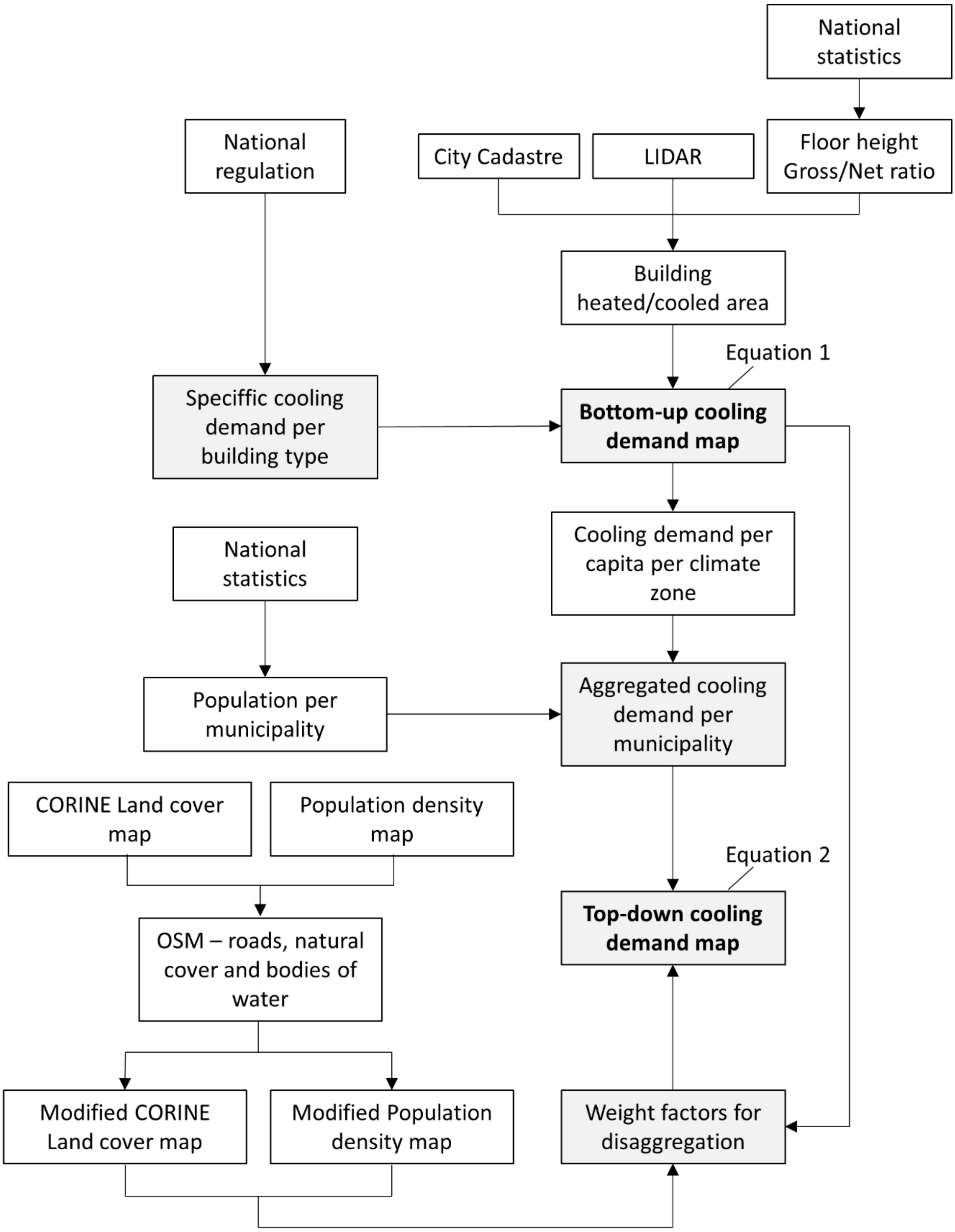

Figure 1 Graphical representation of the proposed method

2.1.Calculation of the specific cooling demand for the selected building types

The speciffic cooling demand of buildings depends on a variety of factors such as the buildings use category, its physical characteristics and the local climate conditions. Due to this variety, it is impossible to utilize the same sets of parameters across multiple countries, or even across multiple regions. In the case of this research, the national technical regulations and algorithms for the calculation of the heating and cooling demands of reference buildings has been utilized. This involves the Technical Regulation on the rational use of energy and thermal protection in buildings ("Tehnički propis o izmjenama i dopunama Tehničkog propisa o racionalnoj uporabi energije i toplinskoj zaštiti u zgradama," n.d.) and the Algorithm for the calculation of necessary energy for heating and cooling according to HRN EN ISO 13790 (Ministry of Physical Planning Construction and State Assets, n.d.).

The required inputs for the calculation of the cooling demand such as the geometry of the building envelope, reference physical characteristics, infiltration and temperature setpoints for the given climate zone, building use category and so on, have been taken from the relevant reference datasets which are available for most European countries and usually published by the relevant ministry. In the case of this research, the data has been taken from surveys conducted by the Ministry of Physical Planning, Constriction and State Assets with the aim to make a comprehensive inventory of the existing national building stock ("Ministarstvo prostornoga uređenja, graditeljstva i državne imovine - Izvješća prema članku 5(2) Direktive 2010/31/EU i članku 6 Uredbe (EU) 244/2012 od 16.1.2012.," n.d.).

2.2. Bottom-up cooling demand mapping for the reference location

Bottom-up cooling demand mapping involves detailed calculations at a very fine resolution and the subsequent aggregation of the obtained data into a predetermined grid. In the case of this research, the cooling demand has initially been calculated on the level of individual buildings and then aggregated to a resolution of 1ha (square grid with 100m sides). The initial building level cooling demand for each individual building has been calculated using the following parameters:

- Footprint area;
- Total height of the building;
- Use category;
- Specific cooling demand per use category;
- Average floor height per use category;
- Net to gross surface area ratio per use category.

The cooling demand has been calculated using Equation 1. In essence, the equation represents a multiplication of the speciffic cooling demand of an individual building based on its type in kWh/m^2 and its net cooled area in m^2.

$$CD = A \cdot NGR \cdot (H/H_F) \cdot CD_S/1000 \qquad \textbf{Equation 1}$$

CD – Total cooling demand [MWh/year]

A – Gross building footprint area [m^2]

NGR – Net area to gross surface area ratio [-]

H – Total height of the building [m]

H_F– Floor height [m]

CD_S – Specific cooling demand [kWh/m^2/year]

Due to the lack of quality reliable data on cooling demand, the parameters involved in the bottom-up calculation of the cooling demand have been calibrated and validated using national statistics on real estate areas and verifiable heat demand. This process includes the calibration of NGR and H_F to the available data on surface areas of the specific building categories in the observed area as well as the calculated heating demand with the available aggregated heat demand data. As cooling is mostly provided through individual air to air heat pumps and cooling demand is rarely fully satisfied, there is no data available which the results of the calculations can be compared to. The cooling demand has been calculated for two climate conditions in the same area and the obtained results have been used to calculate a specific cooling demand per capita and per climate zone. This information has then been utilized to calculate the aggregated cooling demand for each individual municipality taking its climate zone into account.

2.3.Top-down cooling demand mapping and calibration

Top-down cooling demand mapping involves the distribution of aggregated demand over a defined grid using georeferenced data and weight factors. Depending on the availability of data, this process can involve small or large quantities of information of various levels of precision. When detailed data is not available, public databases can be utilised. In the case of this research, the top-down mapping has been conducted using the CORINE land cover maps (Copernicus, n.d.), a global population density map (JRC European Commission, n.d.) and the Open Street maps service ("OpenStreetMap," n.d.).

The CORINE land cover map provides information on the dominant type of land cover over a predefined area. This includes both man-made structures and natural cover. The map does not provide information on the shares or detailed structures of the covers, it only provides the information on the type of the dominant one. This means that, for example, urban tissue is not presented as a mix of buildings, roads and green surfaces but only as one, usually buildings. Due to this limitation, the data obtained from this service needs to be adapted to increase the precision of the overall mapping process. In the case of this research, the Open Street maps service has been utilized to remove roads, green areas and bodies of water from the identified man-made land covers and the result has been reshaped into a 1ha square gird and intersected with the boarders of the municipalities.

The global population density map is based on night-time satellite images which record surface illumination. This has been proven as a good proxy for population density, however it often includes false data such as illuminated streets, parks and, in some cases, flares. To remove as many of these false data as possible, a similar approach has been applied as in the case of the CORINE land cover maps to enhance the precision of the inputs. Data obtained from the Open Street maps service has been utilized to remove roads, parks and bodies of water from the population density maps. The obtained map has been reshaped into a 1ha square grid and intersected with the borders of the municipalities.

Following the previous steps, the cooling demand of each individual grid tile has been calculated using Equation 2**Error! Reference source not found.**.

$$\mathrm{CD}_i = \left(\sum_{n=1}^{n} AC_n \cdot Wf_{Cn} + P_i \cdot Wf_P\right) * \frac{\mathrm{CD}_{mx}}{\sum_{m=1}^{m}\left(\sum_{n=1}^{n} AC_n \cdot Wf_{Cn} + P_m \cdot Wf_P\right)} \quad \textbf{Equation 2}$$

CD_i – Cooling demand of grid tile i [MWh]

n – CORINE land cover categories [-]

AC_n – Area of the modified CORINE land cover category n within grid tile i [m^2]

Wf_{Cn} – Weight factor for the CORINE land cover category n [$1/m^2$]

P – Modified population density in one grid tile [-]

Wf_p – Weight factor for the population density [-]

CD_{mx} – Aggregate cooling demand for municipality x [MWh]

m – grid tile within municipality x [-]

The combination of the modified CORINE land cover and population density maps has been used to distribute the calculated aggregated cooling demand on a municipal level onto a 1ha grid, taking the climate categories of each municipality into account, together with a set of weight factors. The result of this process is a cooling demand map with a resolution of 1 ha covering the entire observed area. The weight factors used in the top-down method have been calibrated using the detailed bottom-up calculation for the reference location to minimize the overall error.

2.4.Assessment of the district cooling potential

The potential for the utilization of district cooling depends on several technical and non-technical factors including but not limited to the existence of district heating and its operational parameters, availability of free cooling sources or potential heat sinks, local prices of labour and equipment and so on. In order to provide a general assessment of the potential, this research has focused on the assessment of the needed margins between the price the cooling energy can be sold for, and the cost incurred for its generation – LCOC (levelized cost of cooling). This margin is calculated using Equation 3

$$(CP - LCOC) \cdot CD_{1km} - L_{g1km} \cdot C_g = 0 \quad \textbf{Equation 3}$$

(CP-LCOC) – Difference between the price and the levelized cost of cooling [EUR/MWh]

CD_{1km} – Cooling demand in a 1km radius [MWh/year]

L_{g1km} – Length of the cooling grid in a 1km radius [m]

C_g – Speciffic cost of the cooling grid [EUR/year/m]

The CP-LCOC value has been determined for each square thus resulting in a clear indication of priority areas for the commercially viable exploitation of district cooling. As 1ha is a relatively small area when district energy is concerned, the cooling demand in the case of this research has been aggregated from a distance of 1 km from each individual 1ha square. This way, the cooling demand potential is taking the situation of the surrounding area into account. The length of the roads and streets in the individual grid squares, again taken from the Open Street maps service, have been used as a proxy for the length of the necessary cooling grid. The lengths have again been aggregated from a distance of 1 km. Finally, in order to determine the cost of the grid per each observed square, the aggregated length has been multiplied by an annual grid cost which includes maintenance and the depreciation of the investment cost.

3. Case study – Calculation

The presented method has been implemented on the case studies of the City of Zagreb (reference area and bottom-up cooling demand mapping) and Croatia (top-down cooling demand mapping and district cooling potential assessment). The City of Zagreb has been selected as the reference area for the detailed bottom-up mapping as it holds roughly 20% of Croatia's population (25% in the metropolitan area) and it has the highest availability of data needed for the implementation of the bottom-up mapping. The method for the bottom-up mapping involves the use of the city's cadastre 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 data has been used to determine each individual building's location, footprint area and use category while the LIDAR recordings have provided the total average height of each building. Using the information on the ratios of total surface areas of individual building categories in urban areas in Croatia, found in the Long term strategy for the refurbishment of the building sector of Croatia (Ministarstvo graditeljstva i prostornog uređenja, 2014), the average floor heights and gross to net surface area ratios have been defined and calibrated. The result of this calibration is presented in Table 1.

Table 1 Net to gross surface area ratios and floor heights for the reference case

Building type	**(NGR) Net to gross ratio [-]**	**(H_F) Floor height [m]**
Residential buildings	0.75	3.00
Commercial buildings	0.70	3.30
Public buildings	0.70	2.80

As no reference cooling demand data exists for either Croatia or the City of Zagreb, the validation of the results has been limited to the surface areas of the individual building categories. The shares of the Residential, Commercial and Public buildings according to (Ministarstvo graditeljstva i prostornog uređenja, 2014) are 67,14%, 23,85% and 9,01% respectively, while the bottom up mapping resulted in shares of 67,06%, 23,77% and 9,17%. The differences between the reference and bottom-up mapping data are less than 1%. For the purpose of this research, it has been assumed that the individual building's net heated area is equal to its net cooled area.

Following the method presented in chapter 2.1, the speciffic cooling demands of the individual building categories have been calculated both for Croatia's continental and coastal climates. The results of this calculation as well as the individual building categories can be found in Table 2. The speciffic cooling demands and net cooled areas per building have been used to calculate the final cooling demand for the City of Zagreb. Since Croatia has two distinct climate zones, both sets of speciffic cooling demands have been used thus creating a real (continental) and virtual (costal) cooling demand map for Zagreb as well as the speciffic cooling demands per population asnd per climate type. Using this information and the total population of each municipality, the total cooling demand has been calculated for each one.

Table 2 Speciffic cooling demand per building type and climate zone

Building type	**Specific cooling demand - CD_s [kWh/m2]**	
	Continental	**Coastal**
Multiapartment building	54	67
Single-family house	34	45
Office building	17	30
Schools/Universities/Kindergartens	45	45
Hospitality and tourism	80	92
Retail and wholesale buildings	8	18
Hospitals	82	95
Sports and recreation	10	10

As no detailed data, such as a building census or official spatial data on building or population density, energy demand and so on, exists for Croatia, publicly available spatial databases have been used. As mentioned in chapter 2.3, three key databases have been used in the process of top-down mapping:

1. CORINE land cover map (Copernicus, n.d.);
2. Global Human Settlement global population density map (JRC European Commission, n.d.);
3. Open Street maps service (“OpenStreetMap,” n.d.)

The qGIS ("QGIS project!," n.d.) tool has been used in this research to implement all GIS related operations. As described previously, the datasets are not necesarraly in the needed resolution and in some cases contain false data. Due to this, the inputs need to be modified and prepared for the use in the described method. This involves the removal of roads, bodies of water and natural cover from the land cover and population density maps as well as their recalculations into the municipal borders and the 1ha grid resolution. Figure 2 presents the bodies of water, natural cover and streets and roads to be removed from the land cover and population density maps for the City of Zagreb (continental climate) and City of Rijeka (coastal climate).

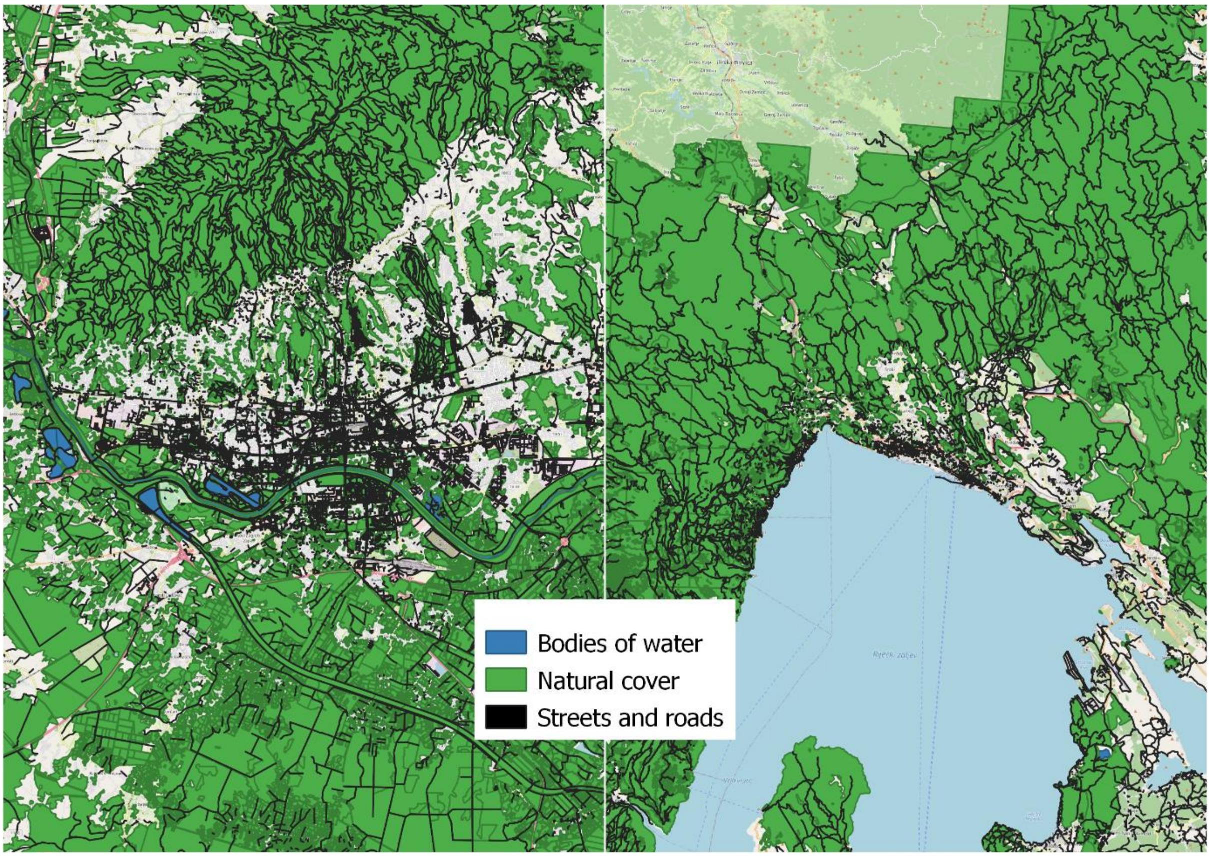

Figure 2 Bodies of water, natural cover and streets and roads to be removed from the land cover and population density maps (Left: City of Zagreb, Right: City of Rijeka)

Figure 3 and Figure 4 present the original and modified CORINE land cover and population density maps for the same two locations as Figure 2. As it can be seen, the modified maps include gaps in locations which are not covered by buildings, such as streets and roads, natural cover and bodies of water.

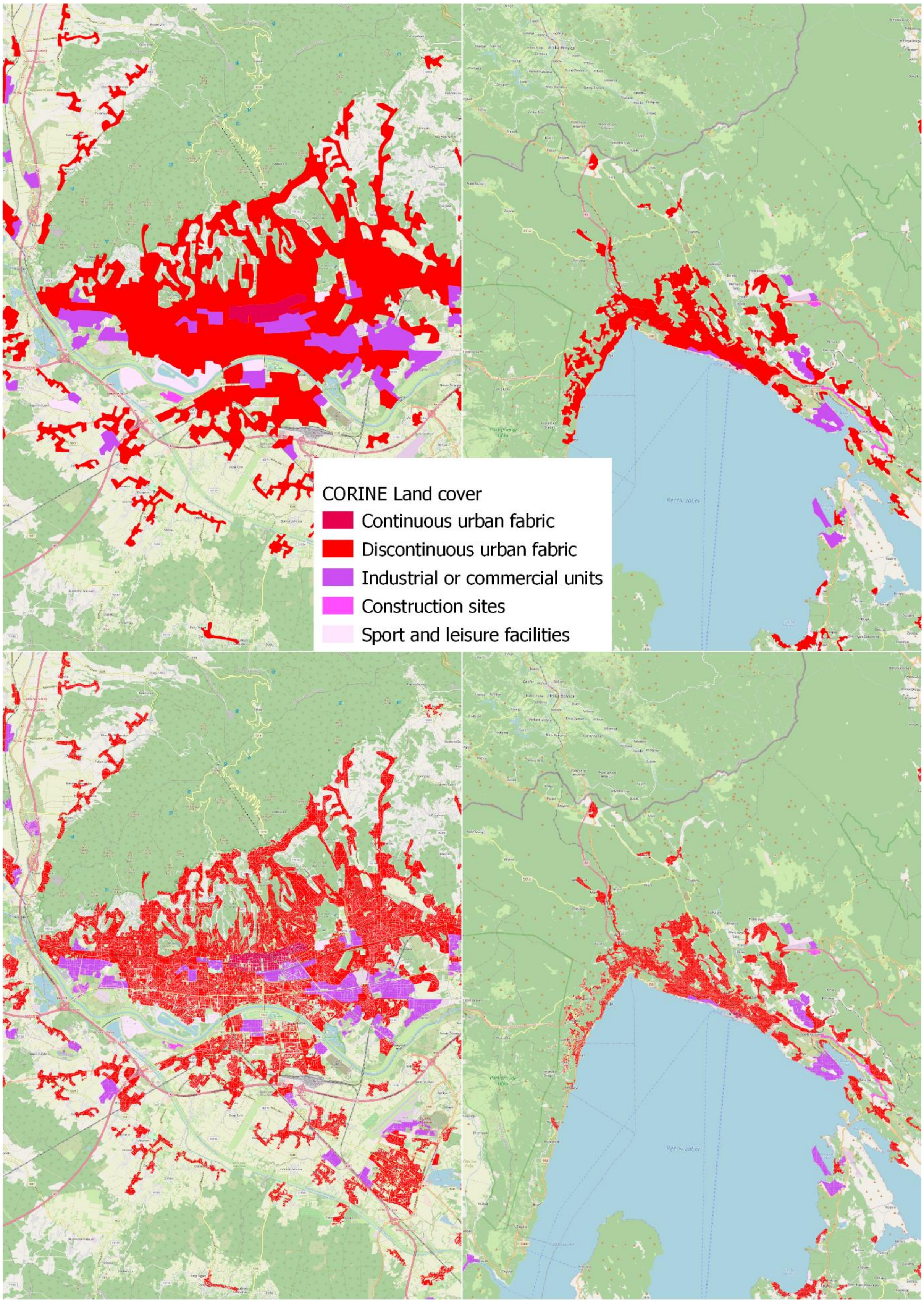
CORINE Land cover
Continuous urban fabric
Discontinuous urban fabric
Industrial or commercial units
Construction sites
Sport and leisure facilities

Figure 3 CORINE land cover map (Top left: City of Zagreb, Top right: City of Rijeka) and modified CORINE land cover map (Bottom left: City of Zagreb, Bottom right: City of Rijeka)

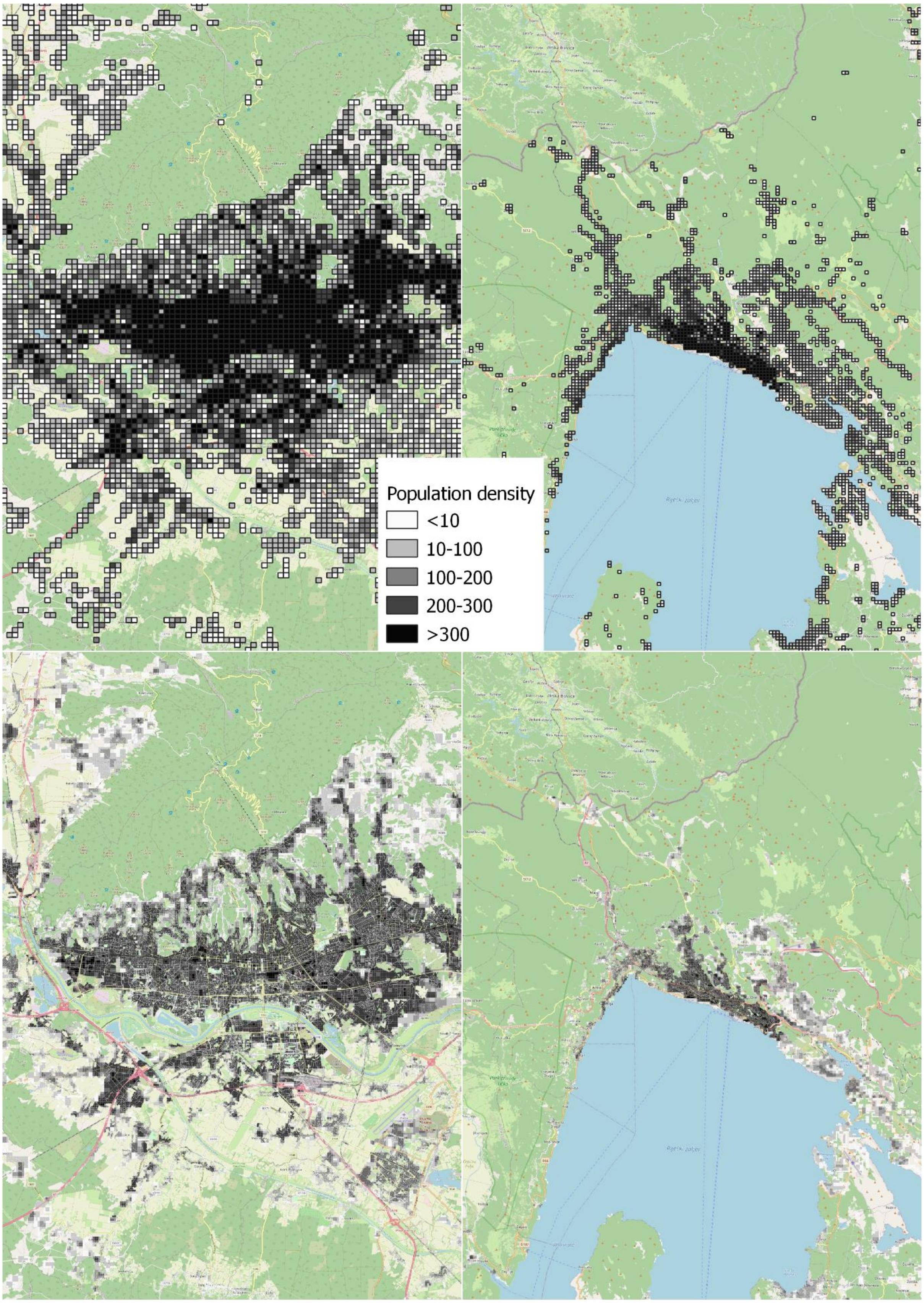
Population density
<10
10-100
100-200
200-300
>300

Figure 4 Population density map (Top left: City of Zagreb, Top right: City of Rijeka) and modified population density map (Bottom left: City of Zagreb, Bottom right: City of Rijeka)

As the final step of the calculation, the data from the modified population density and CORINE land cover maps as well as the aggregated municipal level cooling demands have been added to a 1ha resolution grid. Weight factors have been assigned to each relevant category of the CORINE land cover map (Continuous urban fabric, Discontinuous urban fabric, Industrial or commercial units, Construction sites and Sport and leisure areas) and the population density and using these factors, the aggregated cooling demand of each municipality has been spatially distributed. The weight factors have been determined using an iterative process with the goal of minimising the sum of absolute differences between the individual cooling demands on a 1ha resolution calculated using the bottom-up and top-down methods.

Table 3 presents the final calibrated weight factors for the five relevant CORINE land cover categories and for the population density.

Table 3 Final weight factors

Category	**Weight factor**
Continuous urban fabric	0,226
Discontinuous urban fabric	0,043
Industrial or commercial units	0,006
Construction sites	0,002
Sport and leisure areas	0,002
Population density	7,118

The calculated bottom-up and top-down cooling demand values have been added to a grid containing data on the length of roads within each 1 ha grid. Following that, the total top-down and bottom-up cooling demands as well as the lengths of roads within a 1km radius of the centroids of each 1 ha grid have been summed up into new data sets for the assessment of the viability of district cooling as per the method presented in chapter 2.4.

Table 4 presents a summary of the input data used to develop the top-down and bottom-up cooling demand maps for the purpose of this research.

Table 4 List of inputs used in the development of the bottom-up and top-down cooling demand maps

Input	File format	Comment
Digital cadastre of the City of Zagreb	.shp - georeferenced vector file	Data obtained from the data owner. Used to determine the location, type and footprint area of each building within the reference area.
LIDAR recordings of the City of Zagreb	.dwg – georeferenced raster file	Data obtained from the data owner. Used to determine the total average height of each individual building within the reference area.
Total population per municipality in Croatia	.csv – coma separated values	Publicly available data. Used to calculate the aggregated reference cooling demand of each municipality within the case study area.
Climate zone of each Croatian municipality	.csv – coma separated values	Publicly available data. Used to calculate the aggregated reference cooling demand of each municipality within the case study area.

CORINE Land cover map	.shp – georeferenced vector file	Publicly available data. Used to disaggregate the aggregated cooling demand from a municipal level to the final resolution.
Global Human Settlement global population density map	.dwg – georeferenced raster file	Publicly available data. Used to disaggregate the aggregated cooling demand from a municipal level to the final resolution.
Open street maps service – streets and roads	.shp – georeferenced vector file	Publicly available data. Used to modify the CORINE Land cover map and the Global Human Settlement global population density map.
Open street maps service – bodies of water	shp – georeferenced vector file	Publicly available data. Used to modify the CORINE Land cover map and the Global Human Settlement global population density map.
Open street maps service – natural cover	shp – georeferenced vector file	Publicly available data. Used to modify the CORINE Land cover map and the Global Human Settlement global population density map.

4. Results and discussion

The final Top-down cooling demand map of Croatia at a resolution of 1 ha is presented in Figure 5. Examples of 4 Croatian cities are presented, 2 continental (top) and 2 costal (bottom).

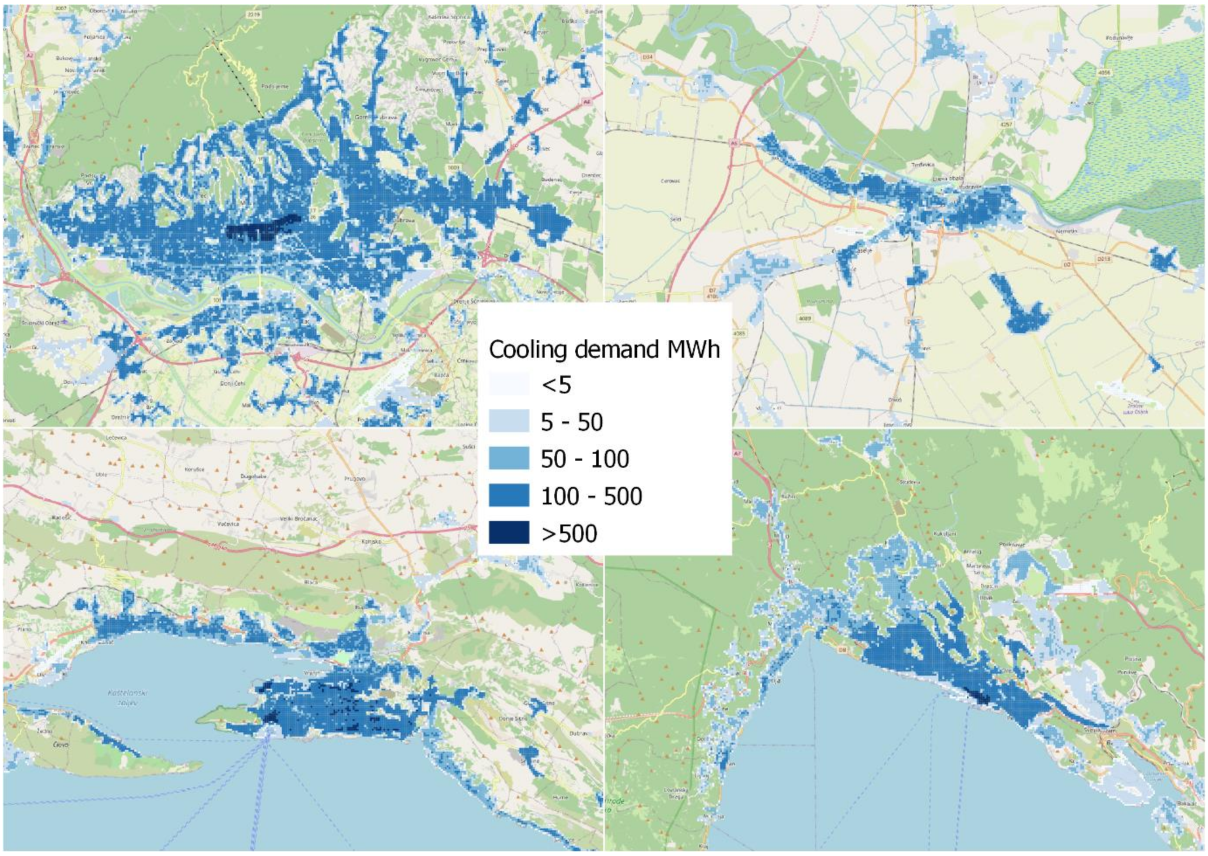

Figure 5 Final Bottom-up cooling demand map (Top left: Zagreb, Top right: Osijek, Bottom left: Split, Bottom right: Rijeka)

Figure 6 shows the comparison of the bottom-up and top-down cooling demand maps for the City of Zagreb. It is evident that the bottom-up map provides a more diverse distribution of the demand as seen from a less uniform distribution compared to the top-down. This is expected due to the diversity of the speciffic cooling demands for the various building categories as well as from the relatively flat distributions of the land use and population densities. Despite that, the top-down map has identified the locations of the cooling demand as well as the critical hotspots which should be investigated further. In order to assess the overall accuracy of the top-down map, the resulting potentials for the utilisation of district cooling have been compared for the case of the City of Zagreb using both mapping methods.

Figure 7 presents this comparison. The figure presents the CP-LCOC values calculated using the Top-down (top) and Bottom-up (bottom) methods assuming the cost of cooling network at 500 EUR/m. The values represent the margin, or the difference in the price of cooling compared to the levelized cost of cooling, needed for the system to be viable. Darker colours in the figure present locations in which district cooling is more viable. Some differences can again be spotted however the main trends have been captured well. The primary hot spot for district cooling potential has been well recognised in both cases (the city centre with the highest density of buildings and population). In order to assess the sensitivity of the results to the assumed distribution network cost, the calculation has been repeated at grid costs of 250, 500, 750 and 1.000 EUR/m of trench length. As the grid costs vary greatly depending on the pipe diameter, type of terrain the trench must traverse and the local costs of labour, a wide range of specific costs has been selected. According to (Möller, Wiechers, Persson, Grundahl, & Connolly, 2018), the grid costs can vary from 658,4 EUR/m to 1551.2 EUR/m for pipe diameters ranging from 0.1 to 0.3m in Sweden. The authors have confirmed, trough informal conversations with representatives of the Croatian district heating operators, that the average prices for district heating grids in Croatia range from 200 to 1.000 EUR/m depending on the type of terrain and pipe diameter.

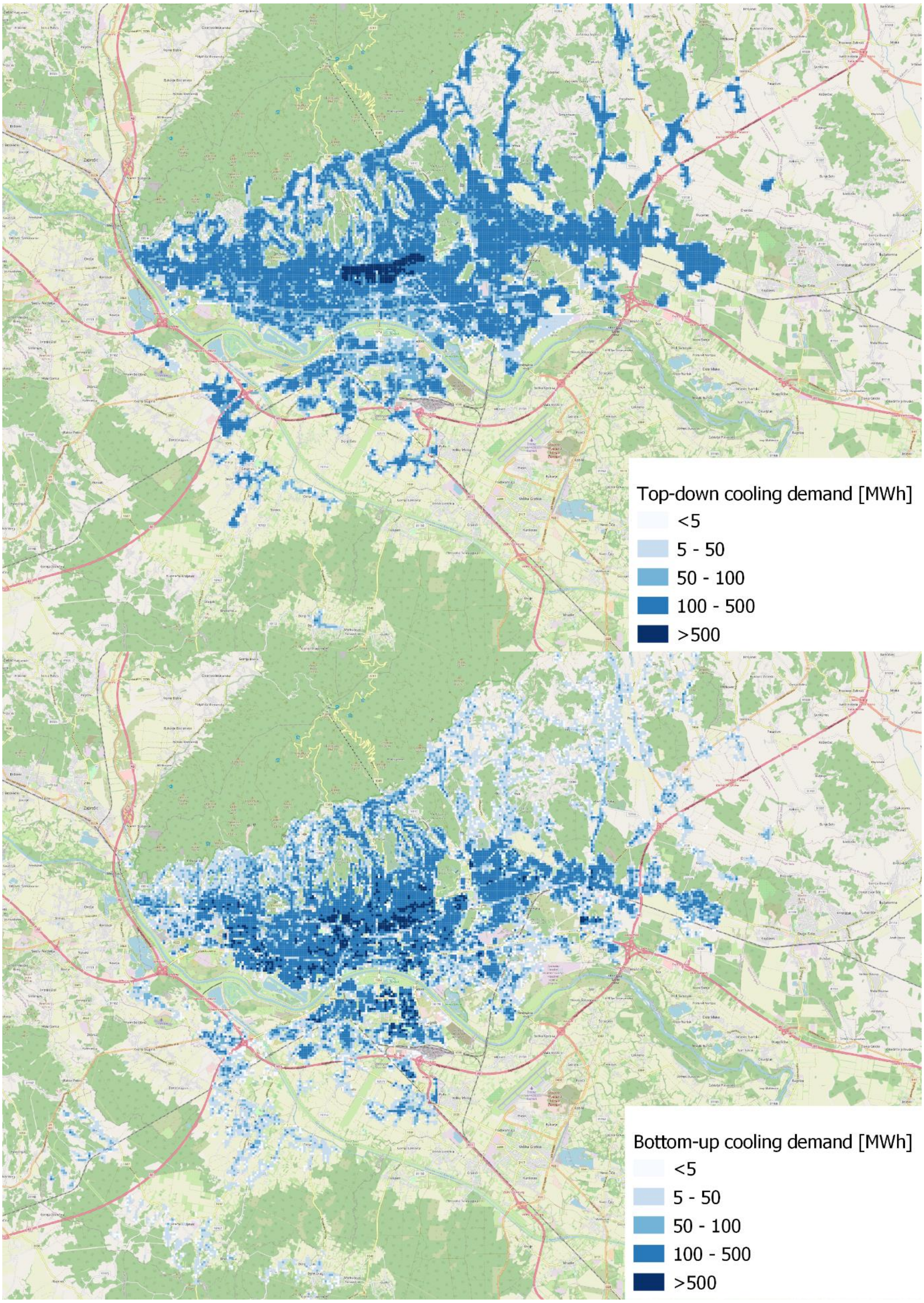

Figure 6 Comparison of the top-down (top) and bottom-up (bottom) cooling demand maps for the City of Zagreb

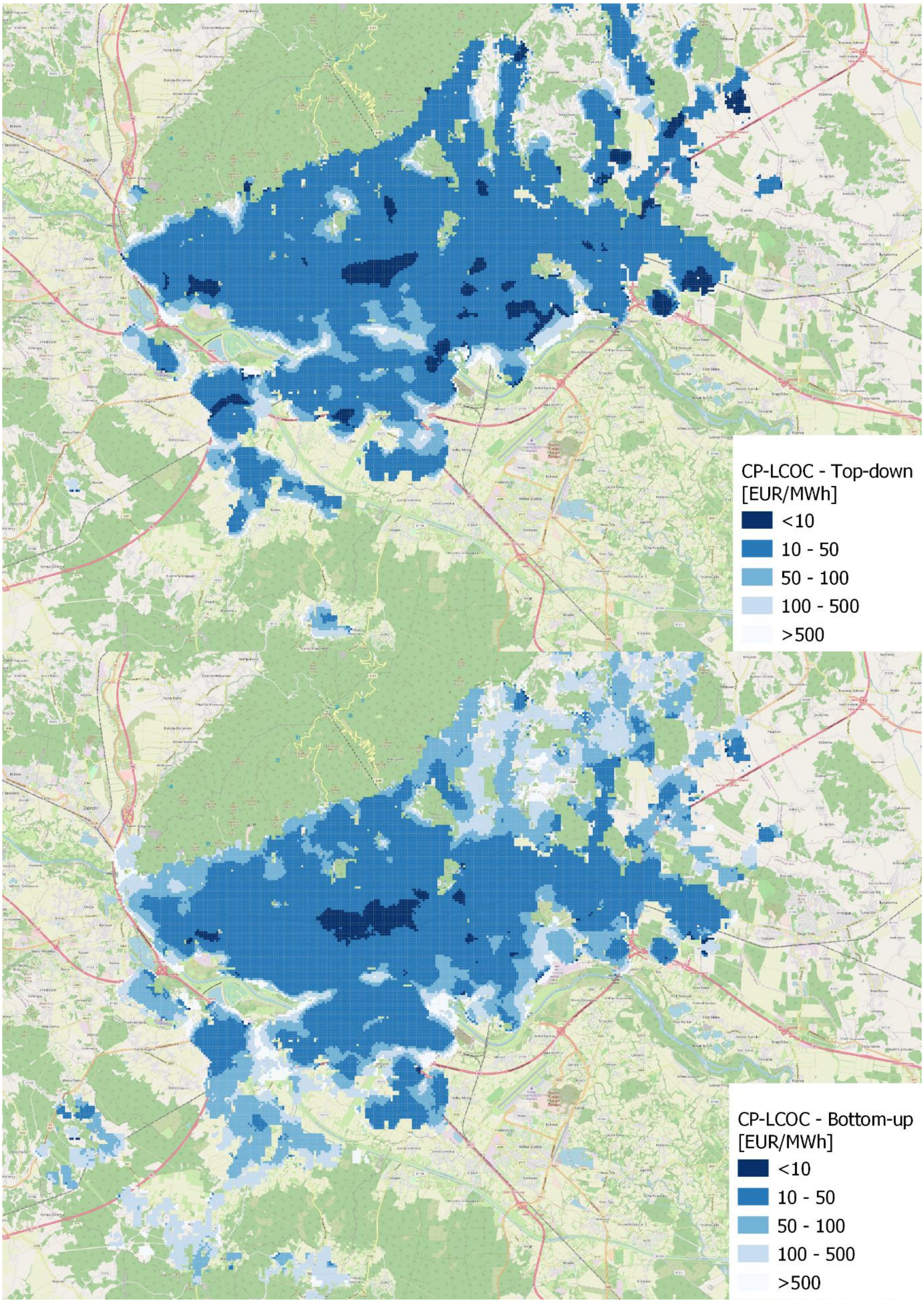

Figure 7 Comparison of the viability of district cooling for the City of Zagreb (Top: Top-down, Bottom: Bottom-up)

Table 5 presents the results of the sensitivity analysis as well as a comparison of the bottom-up and top-down mapping results. As expected, higher grid costs greatly reduce the viability of district cooling. For example, at a CP-LCOC level of 20 EUR/MWh, 72,10% of the total cooling demand in the City of Zagreb could be covered with district cooling if the grid cost equals 250 EUR/m. This goes down to 34,11%, 16,98% and 10,21% in the cases when the grid cost is increased to 500, 750 and 1.000 EUR/m respectively.

Table 5 Sensitivity assessment off the viability of district cooling to the cost of the cooling network – Bottom-up and Top-down results for the City of Zagreb

CP-LCOC [EUR]	**250 EUR/m**		**500 EUR/m**		**750 EUR/m**		**1.000 EUR/m**	
	BU	TD	BU	TD	BU	TD	BU	TD
<2	0,23%	0,36%	0,23%	0,07%	0,23%	0,04%	0,23%	0,02%
<5	10,21%	11,12%	0,24%	0,98%	0,23%	0,25%	0,23%	0,12%
<10	34,11%	41,71%	10,21%	11,12%	0,84%	3,83%	0,24%	0,98%
<20	72,10%	89,57%	34,11%	41,71%	16,98%	19,77%	10,21%	11,12%
<30	86,42%	97,58%	56,76%	73,86%	34,11%	41,71%	20,91%	24,81%
<50	95,41%	99,35%	80,68%	95,32%	62,65%	80,77%	44,80%	60,26%
<100	98,32%	99,85%	95,41%	99,35%	89,37%	98,27%	80,68%	95,32%
<200	98,79%	99,95%	98,32%	99,85%	97,13%	99,66%	95,41%	99,35%
<500	99,04%	99,99%	98,85%	99,96%	98,71%	99,93%	98,57%	99,89%
<1.000	99,10%	100,00%	99,04%	99,99%	98,92%	99,98%	98,85%	99,96%

The comparison between the bottom-up and the top-down results presents a consistent overestimate of the viability of district cooling in the case of the top-down mapping. This is evident as the values are higher across the board and especially when lower speciffic grid costs are utilized in the calculation, due to the stronger impact of the cooling demand, and with that the differences between the bottom-up and the top-down mapping methods, on the results. The difference between the two sets of values is reduced as the grid cost is increased. For example, at a CP-LCOC level of 20 EUR/MWh the bottom-up values for the share of cooling which is viable for district cooling equals 72,19%, 34,11%, 16,98% and 10,21% in the cases of grid costs of 250, 500, 750 and 1.000 EUR/m respectively. In the case of top-down, the values are 89,57%, 41,71%, 19,77% and 11,12%. Based on the observed differences, it is evident that the method is not suitable for detailed assessments for the purpose of the design of individual district cooling systems, however it is capable of identifying hot-spots of increased demand and potential for the exploitation of district cooling. This assessment can serve as a basis for further in-depth analysis of smaller areas which will in turn require high quantities of data and provide more precise findings.

Figure 8, Figure 9, Figure 10 and Figure 11 present the results of the assessment of the viability of district cooling for grid costs of 250 EUR/m, 500 EUR/m, 750 EUR/m and 1.000 EUR/m respectively, for four Croatian cities, two continental and two costal. The results demonstrate both a strong impact of the grid costs and of the climate conditions on the overall viability of district cooling. The two coastal cities are both much smaller and less densely populated than Zagreb and they still maintain a much stronger and more consistent viability for district cooling as the grid costs increase.

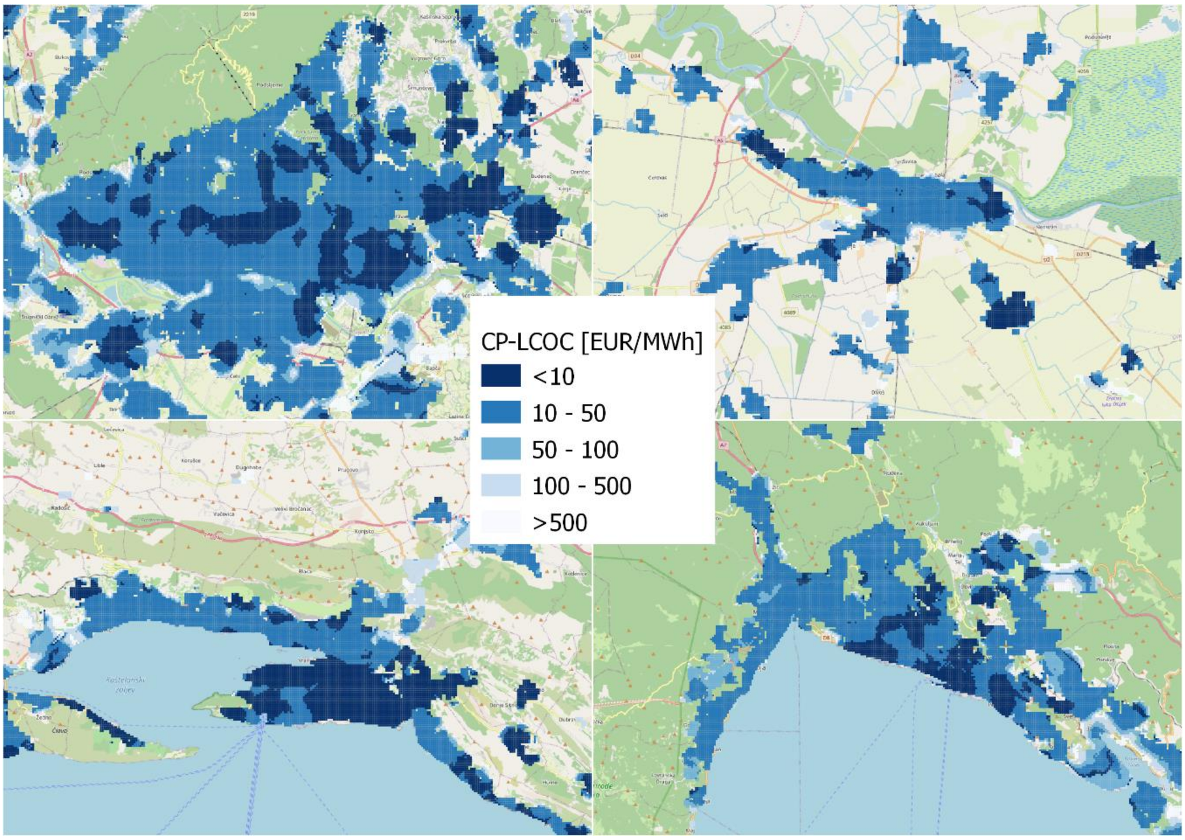

Figure 8 Viability of district cooling at a grid price of 250 EUR/m (Top left: Zagreb, Top right: Osijek, Bottom left: Split, Bottom right: Rijeka)

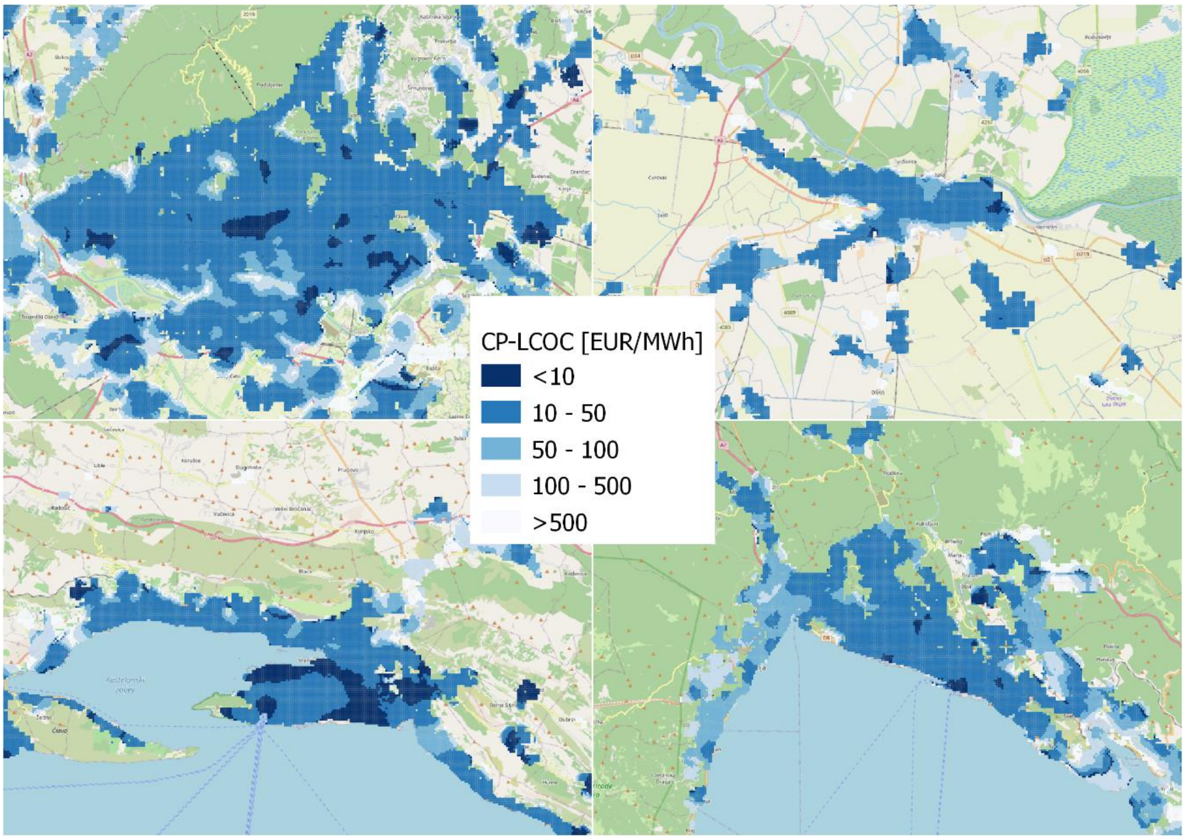

Figure 9 Viability of district cooling at a grid price of 500 EUR/m (Top left: Zagreb, Top right: Osijek, Bottom left: Split, Bottom right: Rijeka)

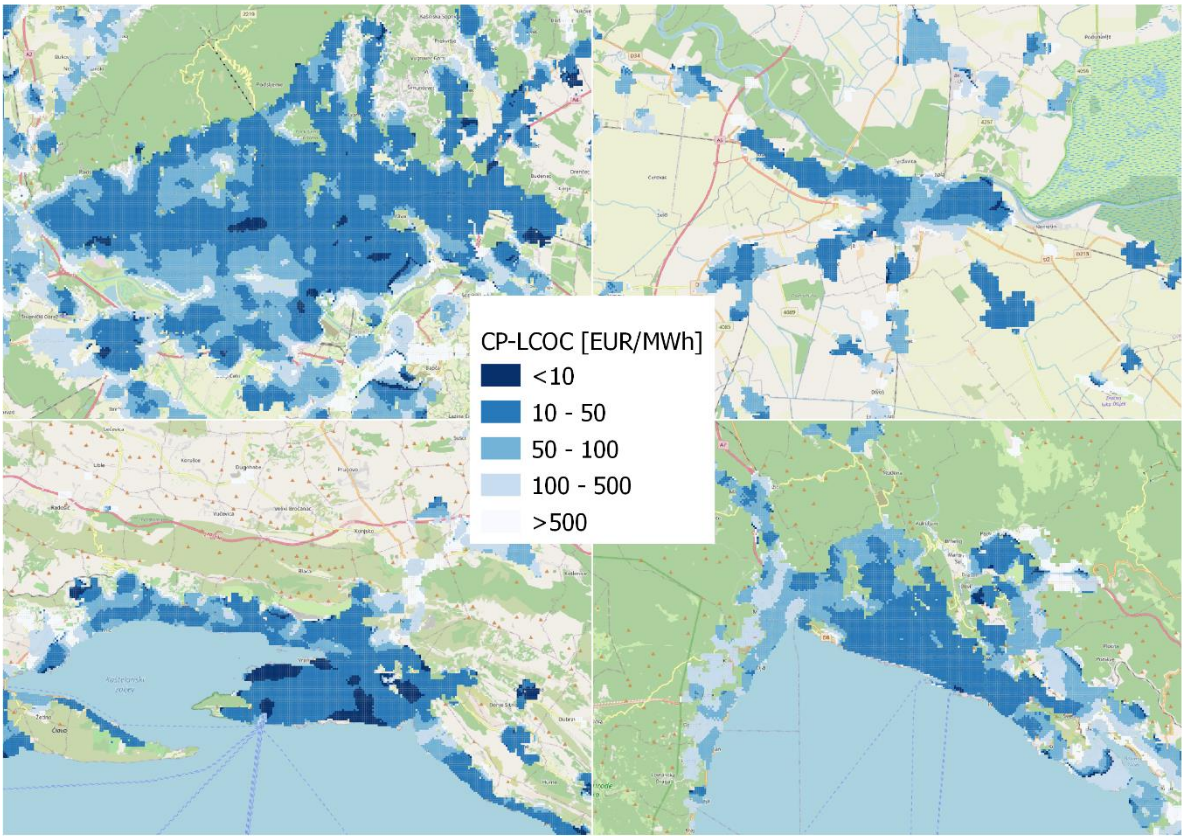

Figure 10 Viability of district cooling at a grid price of 750 EUR/m (Top left: Zagreb, Top right: Osijek, Bottom left: Split, Bottom right: Rijeka)

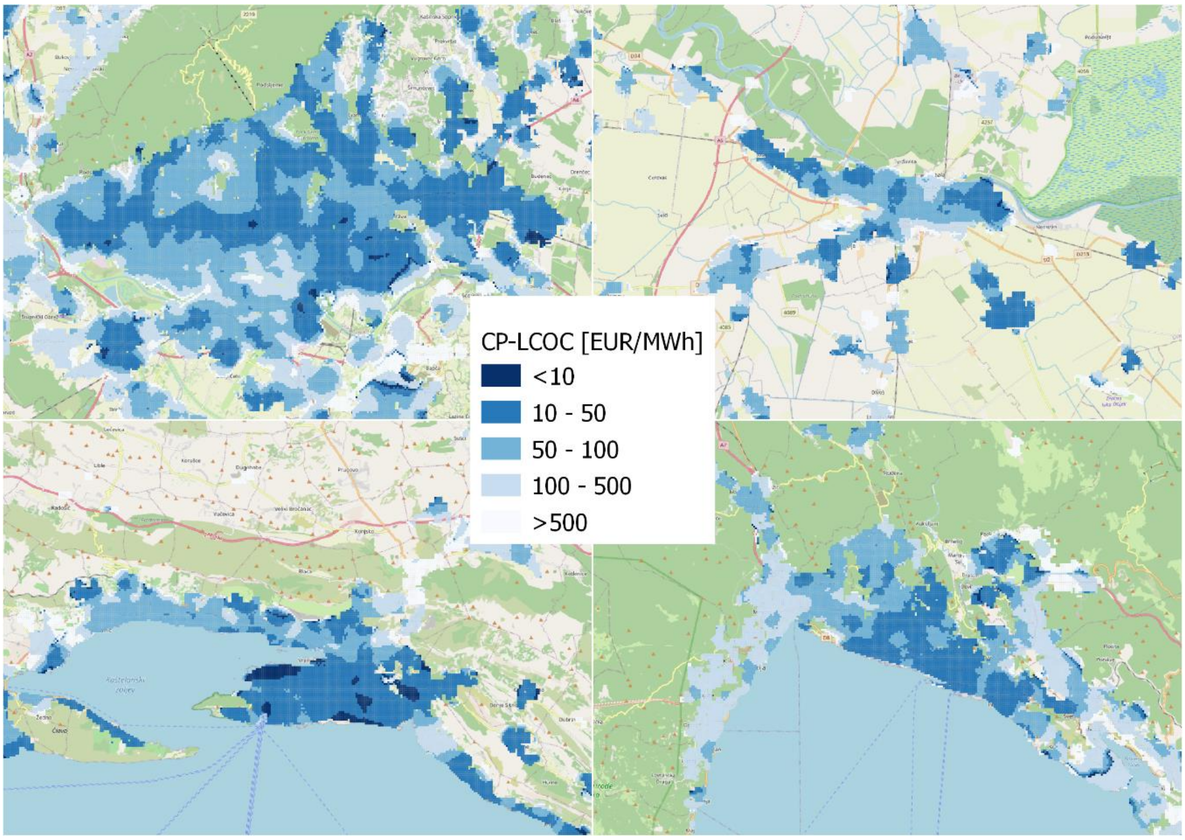

Figure 11 Viability of district cooling at a grid price of 1000 EUR/m (Top left: Zagreb, Top right: Osijek, Bottom left: Split, Bottom right: Rijeka)

Table 6 demonstrates the same results as the previous four figures. It presents a strong potential for the utilisation of district cooling in Croatia. At CP-LCOC levels of below 10 EUR/MWh, between 1,5 and 26,43% of the overall cooling demand in the country could be feasibly supplied by district cooling, depending on the grid costs. These shares increase to a range of 15,76 to 87,86% if the level is increased to 30 EUR/MWh.

Table 6 Results of the assessment of the viability of district cooling – Top-down results for Croatia

CP-LCOC [EUR]	250 EUR/m	500 EUR/m	750 EUR/m	1.000 EUR/m
<2	0,98%	0,29%	0,17%	0,13%

<5	7,26%	1,50%	0,69%	0,42%
<10	26,43%	7,26%	3,05%	1,50%
<20	69,96%	26,43%	12,72%	7,26%
<30	87,85%	50,87%	26,43%	15,76%
<50	96,44%	81,30%	58,16%	39,09%
<100	99,11%	96,44%	90,59%	81,30%
<200	99,67%	99,11%	98,12%	96,44%
<500	99,91%	99,76%	99,58%	99,36%
<1.000	99,97%	99,91%	99,83%	99,76%

5. Conclusion

The decarbonisation of Europe's buildings is key to its long-term sustainable development. Although most of their energy demand is linked to space heating and the preparation of domestic hot water, the provision of energy for cooling is gaining importance, and with that so is the viability of district cooling. The research within this paper demonstrates a four-step approach for cooling demand mapping and the assessment of district cooling potential with an emphasis on the utilization of publicly available data. The method utilizes a combination of spatially distributed and aggregated datasets and a top-down and bottom-up approach to generate a 1ha resolution cooling demand map and a spatial assessment of the viability for the utilization of district cooing of a large geographic area. The spatial assessment of the viability of district cooling utilizes the difference between the price of cooling and the LCOC instead of fixed costs and prices allowing for a great deal of flexibility in terms of local parameters such as technology, energy sources and prices. The presented method has been implemented on the case study of Croatia (top-down) and the City of Zagreb (bottom-up).

The results of the method do present a consistent overestimate of the potential for district cooling of the top-down compared to the bottom-up mapping; however, this is mostly evident in cases when the assumed cost of the district cooling grid is low (250 EUR/m in the case of this research) and when the price of cooling is only marginally higher than the LCOC. Overall, the method provides a flexible tool for the assessment of the viability of district cooling in various climate conditions and independent of the availability of high-quality local data. Although the method cannot provide the basis for the design of individual district cooling systems, it can serve as an initial assessment of a broad area for the identification of hot-spots of cooling demand and potential areas for the utilization of district cooling. The future work within this research will include the utilization of the identified potential for district cooling to assess its impact on the overall energy system as well as its potential integration with the heating and power sectors.

References

Alajmi, A., & Zedan, M. (2020). Energy, cost, and environmental analysis of individuals and district cooling systems for a new residential city. *Sustainable Cities and Society*, *54*, 101976. https://doi.org/10.1016/j.scs.2019.101976

ArcGIS. (n.d.). Retrieved October 7, 2019, from https://www.arcgis.com/index.html

Connolly, D. (2017). Heat Roadmap Europe: Quantitative comparison between the electricity, heating, and cooling sectors for different European countries. *Energy*, *139*, 580–593. https://doi.org/10.1016/j.energy.2017.07.037

Copernicus. (n.d.). CORINE Land Cover — Copernicus Land Monitoring Service. Retrieved May 6, 2018, from https://land.copernicus.eu/pan-european/corine-land-cover

Dutt, F., Quan, S. J., Woodworth, E., Castro-Lacouture, D., Stuart, B. J., & Yang, P. P. J. (2017). Modeling algae powered neighborhood through GIS and BIM integration. *Energy*

Procedia, *105*, 3830–3836. https://doi.org/10.1016/j.egypro.2017.03.896

Equere, V., Mirzaei, P. A., Riffat, S., & Wang, Y. (2021). Integration of topological aspect of city terrains to predict the spatial distribution of urban heat island using GIS and ANN. *Sustainable Cities and Society*, *69*, 102825. https://doi.org/10.1016/j.scs.2021.102825

European Commission. (2019). *The Energy Performance of Buildings Directive Factsheet*. Retrieved from https://ec.europa.eu/energy/sites/ener/files/documents/buildings_performance_factsheet.pdf

EUROPEAN COMMISSION. (2018). A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy. Retrieved October 7, 2019, from https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52018DC0773&from=EN

European Environment Agency. (n.d.). Time series of population-weighted heating and cooling degree days averaged over Europe. Retrieved August 20, 2021, from https://www.eea.europa.eu/data-and-maps/daviz/trend-in-heating-and-cooling-2#tab-dashboard-01

Fahlén, E., Trygg, L., & Ahlgren, E. O. (2012). Assessment of absorption cooling as a district heating system strategy - A case study. *Energy Conversion and Management*, *60*, 115–124. https://doi.org/10.1016/j.enconman.2012.02.009

Groppi, D., de Santoli, L., Cumo, F., & Astiaso Garcia, D. (2018). A GIS-based model to assess buildings energy consumption and usable solar energy potential in urban areas. *Sustainable Cities and Society, 40*, 546–558. https://doi.org/10.1016/j.scs.2018.05.005

Hsu, C. Y., Lin, T. Y., Liang, J. De, Lai, C. H., & Chen, S. L. (2019). Optimization analysis of waste heat recovery district cooling system on a remote island: Case study Green Island. *Energy Conversion and Management*, *183*, 660–670.

https://doi.org/10.1016/j.enconman.2019.01.028

Huang, J., Fan, J., & Furbo, S. (2019, July 1). Feasibility study on solar district heating in China. *Renewable and Sustainable Energy Reviews*, Vol. 108, pp. 53–64. https://doi.org/10.1016/j.rser.2019.03.014

Huculak, M., Jarczewski, W., & Dej, M. (2015, May 10). Economic aspects of the use of deep geothermal heat in district heating in Poland. *Renewable and Sustainable Energy Reviews*, Vol. 49, pp. 29–40. https://doi.org/10.1016/j.rser.2015.04.057

Jangid, J., Bera, A. K., Joseph, M., Singh, V., Singh, T. P., Pradhan, B. K., & Das, S. (2016, November 1). Potential zones identification for harvesting wind energy resources in desert region of India – A multi criteria evaluation approach using remote sensing and GIS. *Renewable and Sustainable Energy Reviews*, Vol. 65, pp. 1–10. https://doi.org/10.1016/j.rser.2016.06.078

JRC European Commission. (n.d.). Global Human Settlement. Retrieved October 7, 2019, from https://ghsl.jrc.ec.europa.eu/index.php

Lund, H., Duic, N., Østergaard, P. A., & Mathiesen, B. V. (2018). Smart Energy and District Heating: Special Issue dedicated to the 2016 Conference on Smart Energy Systems and 4 th Generation District heating. *Energy*, *160*, 1220–1223. https://doi.org/10.1016/j.energy.2018.07.012

Meha, D., Thakur, J., Novosel, T., Pukšec, T., & Duić, N. (2021). A novel spatial–temporal space heating and hot water demand method for expansion analysis of district heating systems. *Energy Conversion and Management*, *234*, 113986. https://doi.org/10.1016/j.enconman.2021.113986

Ministarstvo graditeljstva i prostornog uređenja. (2014). *Dugoročna strategija za poticanje ulaganja u obnovu nacionalnog fonda zgrada Republike Hrvatske*. Retrieved from http://ec.europa.eu/energy/efficiency/

Ministarstvo prostornoga uređenja, graditeljstva i državne imovine - Izvješća prema članku 5(2) Direktive 2010/31/EU i članku 6 Uredbe (EU) 244/2012 od 16.1.2012. (n.d.). Retrieved June 20, 2021, from https://mgipu.gov.hr/pristup-informacijama/zakoni-i-ostali-propisi/podrucje-energetske-ucinkovitosti/izvjesca-prema-clanku-5-2-direktive-2010-31-eu-i-clanku-6-uredbe-eu-244-2012-od-16-1-2012/8619

Ministry of Physical Planning Construction and State Assets. (n.d.). *Algorithm for the calculation of necessary energy for heating and cooling according to HRN EN ISO 13790*. Retrieved from https://mgipu.gov.hr/UserDocsImages/dokumenti/EnergetskaUcinkovitost/meteoroloski_podaci/Algoritam_HRN_EN_13790_2017.pdf

Möller, B., Wiechers, E., Persson, U., Grundahl, L., & Connolly, D. (2018). Heat Roadmap Europe: Identifying local heat demand and supply areas with a European thermal atlas. *Energy*, *158*, 281–292. https://doi.org/10.1016/j.energy.2018.06.025

Möller, B., Wiechers, E., Persson, U., Grundahl, L., Lund, R. S., & Mathiesen, B. V. (2019). Heat Roadmap Europe: Towards EU-Wide, local heat supply strategies. *Energy*, *177*, 554–564. https://doi.org/10.1016/j.energy.2019.04.098

Novosel, T., Pukšec, T., Duić, N., & Domac, J. (2020). Heat demand mapping and district heating assessment in data-pour areas. *Renewable and Sustainable Energy Reviews*, *131*, 109987. https://doi.org/10.1016/j.rser.2020.109987

OpenStreetMap. (n.d.). Retrieved October 7, 2019, from https://www.openstreetmap.org/#map=7/50.510/4.475

Oró, E., Taddeo, P., & Salom, J. (2019). Waste heat recovery from urban air cooled data centres to increase energy efficiency of district heating networks. *Sustainable Cities and Society*, *45*, 522–542. https://doi.org/10.1016/j.scs.2018.12.012

Pampuri, L., Cereghetti, N., Strepparava, D., & Caputo, P. (2016). Analysis of the electricity consumptions: A first step to develop a district cooling system. *Sustainable Cities and Society*, *23*, 23–36. https://doi.org/10.1016/J.SCS.2016.02.015

QGIS project! (n.d.). Retrieved May 18, 2017, from http://www.qgis.org/en/site/

Rahmouni, S., Settou, N., Negrou, B., & Gouareh, A. (2016). GIS-based method for future prospect of hydrogen demand in the Algerian road transport sector. *International Journal of Hydrogen Energy*, *41*(4), 2128–2143. https://doi.org/10.1016/j.ijhydene.2015.11.156

Shi, Z., Fonseca, J. A., & Schlueter, A. (2021). Floor area density and land uses for efficient district cooling systems in high-density cities. *Sustainable Cities and Society*, *65*, 102601. https://doi.org/10.1016/j.scs.2020.102601

Shi, Z., Hsieh, S., Fonseca, J. A., & Schlueter, A. (2020). Street grids for efficient district cooling systems in high-density cities. *Sustainable Cities and Society*, *60*, 102224. https://doi.org/10.1016/j.scs.2020.102224

Tehnički propis o izmjenama i dopunama Tehničkog propisa o racionalnoj uporabi energije i toplinskoj zaštiti u zgradama. (n.d.). Retrieved June 20, 2021, from https://narodne-novine.nn.hr/clanci/sluzbeni/2020_09_102_1922.html

Thakar, K., Patel, R., & Patel, G. (2021). Techno-economic analysis of district cooling system: A case study. *Journal of Cleaner Production*, *313*, 127812. https://doi.org/10.1016/j.jclepro.2021.127812

United Nations. (2018). *2018 Revision of World Urbanization Prospects*.

van Schijndel, A. W. M. J., & Schellen, H. L. H. (2018). Mapping future energy demands for European museums. *Journal of Cultural Heritage*, *31*, 189–201. https://doi.org/10.1016/j.culher.2017.11.013

Viesi, D., Galgaro, A., Visintainer, P., & Crema, L. (2018). GIS-supported evaluation and mapping of the geo-exchange potential for vertical closed-loop systems in an Alpine valley, the case study of Adige Valley (Italy). *Geothermics*, *71*, 70–87.

https://doi.org/10.1016/j.geothermics.2017.08.008

Yi, C. Y., & Peng, C. (2017). Correlating cooling energy use with urban microclimate data for projecting future peak cooling energy demands: Residential neighbourhoods in Seoul. *Sustainable Cities and Society*, *35*, 645–659. https://doi.org/10.1016/J.SCS.2017.09.016

Zyadin, A., Natarajan, K., Latva-Käyrä, P., Igliński, B., Iglińska, A., Trishkin, M., … Pappinen, A. (2018, June 1). Estimation of surplus biomass potential in southern and central Poland using GIS applications. *Renewable and Sustainable Energy Reviews*, Vol. 89, pp. 204–215. https://doi.org/10.1016/j.rser.2018.03.022