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Quantification of overlapping heating and cooling demand for the feasibility assessment of bi-directional systems over Europe

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A R T I C L E I N F O

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A B S T R A C T

With warmer climate conditions, the growing need to cool down building environment in Europe calls for efficient solutions to solve the heating and cooling demand altogether. To meet such requirement, the bi-directional fifth generation district heating and cooling (5GDHC) system has been proposed in recent years, while having the capability of integrating the renewable and waste energy sources. The overlapping heating and cooling demand, or referred to as the simultaneous demand, is proved as the key pre-requisite to guide the application of 5GDHC through several case studies. However, how large is this overlapping part in the practical building stock and where are the feasible areas for 5GDHC remain unclear. To close the gap, this study assesses the quantities and geographical distributions of overlapping heating and cooling demand across Europe in EU 27, UK, and EFTA countries. Using GIS-based methods and data sources, the study region is split into 28 million hectare-sized units where the overlapping demand is specifically calculated. Moreover, the possible future changes to the heating and cooling demand alone brought by warmer climate, building renovations, and increased cooling area were investigated. The results from reference condition at year 2016 reveal that less than 0.1% of the building stock has DOC larger than 0.3, which is the threshold for 5GDHC being energy efficient. These potential areas are primarily found in city centres involving cooling demands from commercial and industrial processes. In the future scenarios of year 2050, while a better energy performance of buildings and warmer climate may decrease the heating and increase the cooling demand, the overlapping part is only slightly increased by around 5%. Accordingly, around 2500 ha-sized units from the entire study region are found to meet the DOC limit required by the 5GDHC while having large enough demand density to support district energy systems. The presented works geographically identified the potential areas for 5GDHC and can be extended with regional details to serve as the connection between top-level planning and bottom-level case studies.

1. Introduction

Heating and cooling for buildings represent over 20% of the final energy use within the European Union. However, only 23% of this energy is based on renewable energy sources [1], while the burning of fossil fuels is contributing heavily to the carbon emission in Europe. With the goal of the Paris agreement, a set of proposals and measures on replacing the fossil fuels with renewable sources have been adopted by the European Commission [2]. In recent times, due to complex geopolitical issues and unrealistic evaluation of the technical development, the plans to achieve carbon neutrality in a few pioneer cities in Europe are being slowed down [3]. The circumstances have made the decarbonization of the heating and cooling sector more important than ever.

Currently, space and water heating constitute more than 60% of the European heating and cooling demand [4]. Although the share of space cooling demand is only around 2% [5], it is believed to grow in the future due to warming climate, growing population and increasing requirement for better indoor environment [6]. To deal with such changes, the fifth generation district heating and cooling (5GDHC) system, which meets the heating and cooling demand simultaneously via the ultra-low temperature distribution network and building-side heat pumps (HPs), has been proposed in recent years [7]. The key feature of such system is that the distribution network is operated at very low temperature close to the ambient (around 10 °C to 30 °C), which minimizes the thermal losses and creates potentials for waste energy recovery [8]. Hybrid substations with water source HPs and chillers are installed in buildings to lift or reduce the temperature to required heating or cooling levels [9]. Such gradient temperature configuration

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Nomenclature

5GDHC	Fifth generation district heating and cooling
CDD	Cooling degree day
DHC	District heating and cooling
DHW	Domestic hot water
DOC	Demand overlap coefficient
GFA	Gross floor area
GIS	Geographical information system
HDD	Heating degree day
HP	Heat pump
KPI	Key performance indicator
NUTS	Nomenclature of Territorial Units for Statistics
RCP	Representative concentration pathway
RCM	Regional climate model
GCM	Global climate model
REF	Reference
SC	Space cooling
SH	Space heating
TES	Thermal energy storage

assures higher energy and exergy efficiencies compared with traditional centralized heating systems [10]. The system is also known as the *Bi-directional Network* [11,12] or *Cold District Heating Network* [13]. Growing numbers of research works on 5GDHC are found, as reported in the statistical survey of 40 operating systems [14] and the recent review paper on research gaps and challenges [7].

Despite the increasing interest, the feasible area for this novel technology in the practical building stock remains unclear. Being not only a costly but complex system option, the feasibility of the 5GDHC system is influenced by factors from various technical and economic aspects. Yet, several previous works [11,15] were only based on case studies that already have favored conditions for the 5GDHC, as summarized in [16]. To increase the understandings on the system feasibility, key performance indicators (KPIs) were identified and used as evaluations of the applicable conditions [17,18]. The main competence of 5GDHC system is serving the heating and cooling demand simultaneously. Thereby, the overlapping heating and cooling demand is regarded as a pre-requisite for making the 5GDHC system feasible, as represented by the demand overlap index (DOC) for different time series [12]. The electricity price and the share of operational cost decide the revenue to cover the high initial cost and largely influence the economic attractiveness of 5GDHC [16]. A summary of the KPIs and their sensitivities on the system performance can be also found in [16]. These works have clearly figured out the favorable conditions for the 5GDHC system on the case-specific level. However, from a broader view, the potentials and roles of the 5GDHC in a whole region or in the European level remains unknown. To solve this, the favored conditions can be evaluated in the practical building stock to guide the applications of 5GDHC, which is the main research gap. More specifically, there is no knowledge on how large the overlapping heating and cooling demand is in Europe. Without such information, the future applications of the 5GDHC system are unclear.

To quantify the overlapping demand and the feasibility of 5GDHC system, high-resolution data on heating and cooling demand is needed. In recent years, the development of Geographic Information System (GIS) methodologies has created possibilities of assessing the end-use energy demand density in subtle scales. A summary of GIS-based density studies, classified by the approaches, resolutions, and considered energy demand types, can be found in [19]. Population density, satellite data on building stock, and local database were commonly used as data sources to create the energy density results [20]. For the heating and cooling demand densities, hectare-level data for Europe are found in several projects [21,22]. However, none of the previous works have addressed the quantities of overlapping demand and their distributions.

On another note, it is unequivocal that the heating and cooling demands will change in the future. Main causes include the global climate change [23], building renovation measures [24], and the increased use of air-conditioners [6,25]. The impacts of climate change, with different climate models and emission pathways, were studied and compared in [26] using the degree day method. The uncertainties induced by different climate models on the building energy performance were estimated by Nik et al. [27]. Concerning the building renovation project, the current annual deep renovation rate stands at only 0.2% on average in EU [28], which is far behind the energy saving target to achieve the climate neutrality by 2050. Thereby, the EU commission published the renovation wave strategy in 2020 to double annual energy renovation rates in the next 10 years [29]. The intended changes in heating and cooling demand, the reductions of greenhouse gas emissions, and benefits for individuals and societies, were analyzed in several reports [29,30]. In the meanwhile, the adoption of air-conditioners, which is currently low in EU countries, is about to increase in the future as the consequence of heatwaves [31]. As a result, the corresponding space cooling demand and electricity consumption is also increasing in the future. Despite the wide knowledge on heating and cooling demands alone, the future changes in overlapping demand are still unknown.

To close the gaps, it is clear that while the 5GDHC system is well studied on case-level, there is no knowledge about the feasible areas on the European building stock. The roles of this new technology in the overall heating and cooling demand remains unclear. Furthermore, considering the possible reduction of heating demand and increase of cooling demand, the future potential of bi-directional system requires further notice. In summary, this study presents the assessment of the quantities and distributions of overlapping heating and cooling demand in EU 27, UK, and EFTA countries on hectare-level, via GIS-based methodologies and data sources. The feasible areas that have enough overlapping demand and demand densities to favor the applications of 5GDHC are identified. The future demand changes and their impact on the applications of the 5GDHC system are specifically addressed.

This paper is organized as follows: Section 2 introduces the data sources, future changes in the demand side and the analysis methods. Section 3 explains the assessment results in current scenario and future scenarios, followed by geographical presentations of the 5GDHC regions. Discussions and conclusions are presented in Section 4 and 5, respectively.

2. Methodology

This paper presents a GIS-based approach to spatially and temporally assess the overlapping heating and cooling demand in Europe. Section 2.1 explains the study range and demand distributions. An overview of the methodology framework is shown in Fig. 1. The open data source for demand densities and building floor area on hectare level is explained in Section 2.2. To reflect the future changes of demand, the climate models and building stock changes are introduced in Section 2.3 and 2.4, respectively. Based on demand density data, the methods for analyzing the overlapping demand and feasibility of 5GDHC are presented in Section 2.5.

2.1. Study range

EU 27 countries, UK, and EFTA countries were included in the investigation. The study range and distributions of heating and cooling demand are presented in Fig. 2, based on the data sources stated in Section 2.2. For a direct expression purpose, only the major demand locations are plotted and the complete database can be accessed from [22]. It is seen that the cooling demand is mostly found in Southern European countries. In Northern regions, such demand only exists in the non-residential area of large cities. The country-specific demands under reference and future scenarios are provided in Supplementary Material.

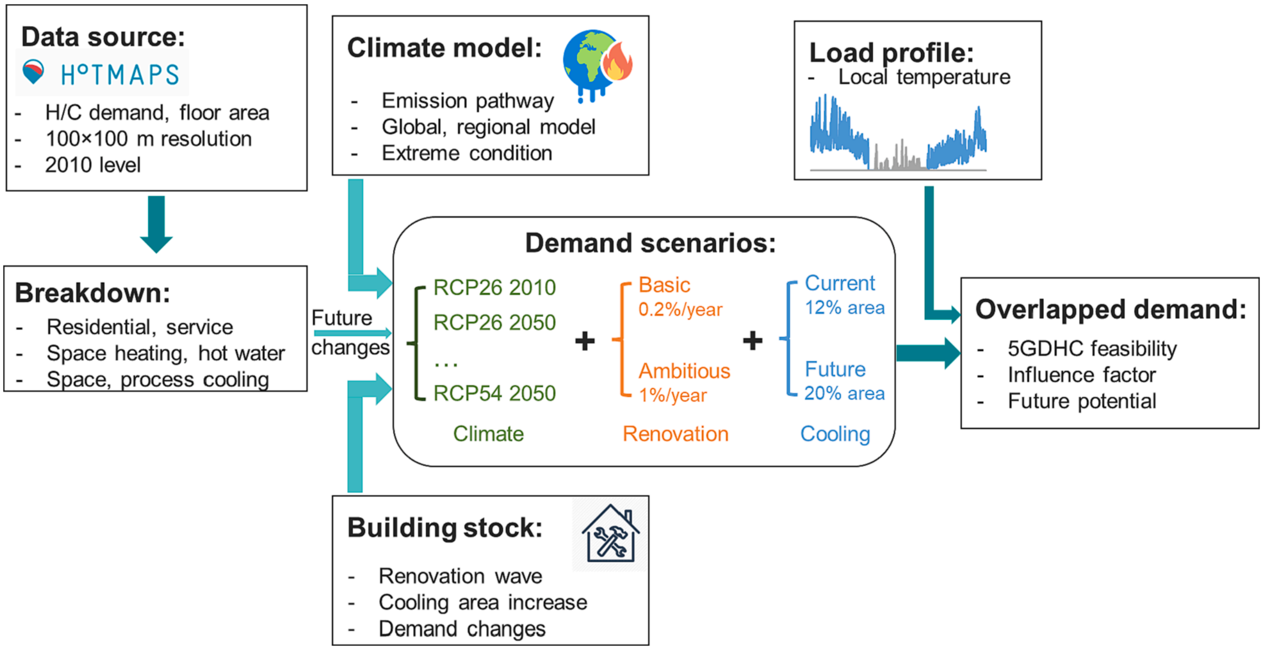

Fig. 1. Flowchart overview of the main methodology.

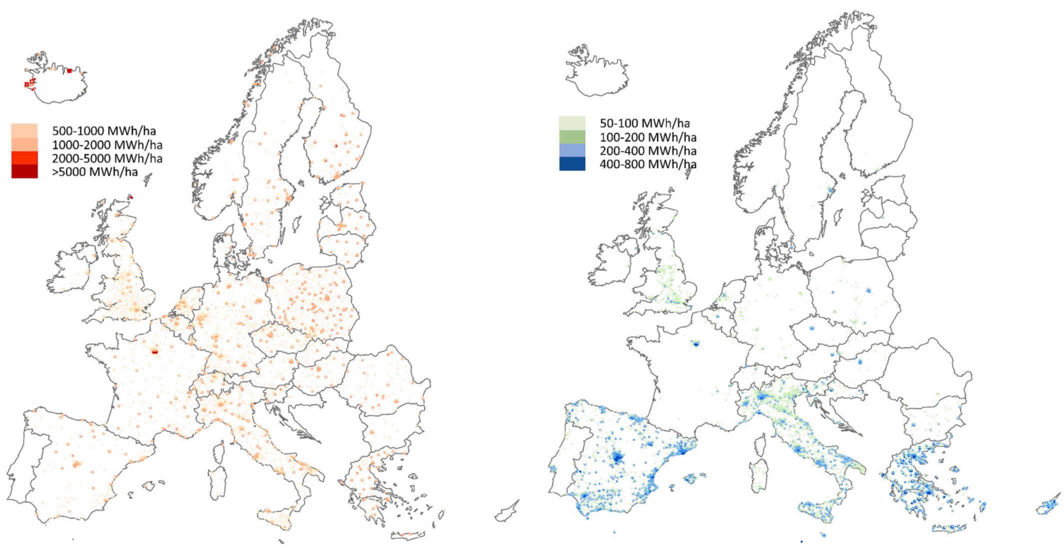

Fig. 2. Distributions of heating (left) and cooling (right) demand in the studied European countries at year 2016.

While the demand for domestic hot water (DHW) exists along the whole year, the length of space heating (SH) and space cooling (SC) period varies among countries due to different climate conditions. The Nordic countries have the longest SH period of around 5800 h, and the shortest SC period of less than 500 h. Conversely, in warmer climate regions such as those Mediterranean islands, the SH period is less than 1,000 h while the SC period is over 5,500 h. As with the future climate changes explained in Section 2.3, the length of SH period is generally shortened, and the SC period is extended.

2.2. Demand density data

The hectare-level demand densities and floor area are derived from the open source toolbox Hotmaps [22]. As a starting point, the toolbox provides the gross floor area (GFA) with a resolution of 100 × 100 m covering the entire investigated European countries [32] at year 2016. Excluding the rural area with no buildings, a total number of 28 million hectare-sized units are included in the database. The data is based on aggregated floor area at country level and is organized considering population density [33], land-use data [34], the European Settlement Map layer [35], and data from OpenStreetMap database. The data associated with buildings is classified into the residential sector and service sector. Furthermore, for the share of buildings per construction period, the soil sealing data for 1975, 1990, 2000, and 2014 from the Global Human Settlement project [36] were used. This section introduces general methodologies, while the detailed processes can be found in the toolbox report [32]. A summary of the main databases is presented in Table 1.

Based on the GFA data, the heating and cooling demand densities were analyzed considering the building stock characteristics, the digital elevation model, the local climate data, and the distribution of population density. Basic statistics on the heating and cooling demand could

Table 1
A brief summary of main databases used in this study.

Name	Description	Database
Demand density	SH, SC, and DHW at hectare level	Hotmaps [22]
Gross floor area	Residential and service	
Climate	Various pathways towards 2050, 12.5 km resolution	CORDEX [43]
Renovation	Annual renovation rate at country level	Renovation wave [30]

be extracted from the toolbox for the EU at regional/local level. The toolbox classifies the energy demand by SH, SC, and DHW, as further shown in Fig. 5. The main source for the useful energy demand of these sectors is Invert/EE-Lab database [37]. However, as pointed out in previous works [5,19], the assessment of SC demand density is difficult because the cooled floor area is hardly known. In this study, the heated and cooled floor area are based on multiple sources [38–40] and are cross-checked. The resulting cooled floor area ratios for the residential and service sector are 6.7% and 27.4%, respectively, which are close to the estimations in [5]. With the impact of heatwaves in Europe, this study also considers possible growth of cooled area in the future, as further explained in Section 2.4.

Besides the demand for cooling down the indoor air space, the refrigeration demand required by specific processes in service buildings, such as the supermarket and data center, is also considered in this study. Waste heat that has low temperature level of around 30–40 °C is usually generated with these processes. Thereby, the demand is also noted as process cooling, and is considered an important factor in the 5GDHC system [17,18]. For clarification, the heating and cooling demand in the industrial sector are not included in this work. Due to the lack of locally available data, a general proximation methodology is used. The process cooling density is calculated based on GFA density of service building, specific building types, empirical cooling demand for each building type, and aggregated country-level demand [41,42]. The process cooling is not considered in residential buildings.

It shall be noted that the main aim of this paper is revealing the overlapping demand at regional level, as the applied databases can reflect the demand changes at the resolution of 100 × 100 m. The feasibility of 5GDHC at a specific location requires more bottom-level investigations and designs. Still, the general future trend about overlapping demand and the potential areas of 5GDHC is evaluated using methodologies explained in Sections 2.3 and 2.4. Limitations and future research directions are further discussed in Section 4.

As reported in the toolbox document [32], all collected information on space heating, space cooling and domestic hot water have been filtered and statistically evaluated. According to the number of sources, the coefficient of variation has been used as statistical indicator of uncertainty and to exclude values outside a range of plus or minus the standard deviation around the average. The filtered values are used in this study. The calculation and analysis were performed in MATLAB, and the geographical presentation was performed using the mapping toolbox.

2.3. Future climate changes

To represent different climate futures, the low and intermediate representative concentration pathway (RCP), namely RCP2.6 and RCP4.5 respectively, are considered in this study. The decade of 2050 is studied as the representative of future checkpoint for reaching the carbon neutrality target [2]. The moderate scenario is based on RCP2.6 and uses the yearly profile that is close to the 10-years average level of 2050s. For RCP4.5, as indicated in previous work [26], the 10-years average level has similar impact on the demand as that of the RCP2.6 scenario. Thereby, the year with the highest annual average air temperature of the 2050s decade is used in this study, as representative of the extreme scenario under RCP4.5. Summary of key characteristics of future changes is provided in Table 2.

The regional climate model (RCM) is capable of simulating geophysical processes in the atmosphere and land surface and is used to downscale the result of the coarse global climate model (GCM). Thereby, every combination of RCM and GCM constitutes a simulation of the future climate scenario. Discussions on the wide choices of RCMs and GCMs and their sensitivities on the projected future climate results can be found in previous works [26,44]. This study has used the RCA4 as the RCM, which has results close to the average level of all models [45]. The model is created by the Rossby Centre, the climate modelling unit of the Swedish Meteorological Hydrological Institute (SMHI). The chosen GCM is ECHAM6, which is a coupled atmosphere–ocean model, developed at the Max-Planck Institute for Meteorology in Hamburg, Germany. The climate models are derived from CORDEX database, which coordinate the science and application of regional climate downscaling through global partnerships [43]. The results are available at 12.5 km^2 resolution.

To quantify the future heating and cooling demand, the degree day method is applied in this study. It is assumed that the changes of space heating and space cooling demand are proportional to the changes of heating degree days (HDDs) and cooling degree days (CDDs) [46], as written in Eq. (1). The future HDDs and CDDs at different scenarios were calculated for all hectare-sized units with 12.5 km^2 resolution. As for the current climate conditions, the year 2016 is chosen, in accordance with the reference year for demand densities and GFA densities. The equations for HDD and CDD are based on [28,46], as presented in Eqs. (2) - (5). For the DHW and process cooling demands, no changes were considered for the future due to their relatively stable demand profiles.

$$\frac{Q_{SH,2050}}{Q_{SH,2016}} = \frac{HDD_{2050}}{HDD_{2016}} \tag{1}$$

where $Q_{SH,2016}$ and $Q_{SH,2050}$ are the cumulative SH demand in year 2016 and 2050, respectively.

There have been discussions on the choice of base temperature T_b [47]. In this study, the T_b for calculating the HDD and CDD is set as 15.5 °C and 22 °C, respectively, as commonly adopted for the European building stock. The HDD is calculated for the heating period (Oct 1 to March 31), and the CDD is calculated for the cooling period (Apr 1 to Sep 30). The annual HDD and CDD is the aggregated result of daily values during each period.

$$HDD_i = \begin{cases} T_b - T_M & \\ \dfrac{T_b - T_N}{2} - \dfrac{T_X - T_b}{4} & \\ \dfrac{T_b - T_N}{4} & \\ 0 & \end{cases} \text{if} \begin{cases} T_b \geq T_X \\ T_M \leq T_b < T_X \\ T_N \leq T_b < T_M \\ T_b \leq T_N \end{cases} \tag{2}$$

$$HDD = \sum_{i=1}^{183} HDD_i \tag{3}$$

Table 2
Summary of key characteristics of future changes.

Category	Name	Description
Climate	2050	RCP 2.6. The year close to the 10-years average level
	2050e	RCP 4.5. The extreme year with highest annual average temperature
Renovation	Slow	Current speed, deep renovation 0.2%
	Fast	Ambitious speed, deep renovation 1%
Cooling area	Current	12% of gross floor area
	Increase	20% of gross floor area

$$CDD_i = \begin{cases} 0 \\ \frac{T_X - T_b}{4} \\ \frac{T_X - T_b}{2} - \frac{T_b - T_N}{4} \\ T_M - T_b \end{cases} \text{if} \begin{cases} T_b \geq T_X \\ T_M \leq T_b < T_X \\ T_N \leq T_b < T_M \\ T_b \leq T_N \end{cases} \tag{4}$$

$$CDD = \sum_{i=1}^{183} CDD_i \tag{5}$$

where T_M, T_X, and T_N are the mean, maximum, and minimum temperature in day *i*, respectively.

2.4. Building stock changes

Based on the Global Human Settlement project [36], the share of buildings per construction period was analyzed by comparing the share of soil sealed by buildings against the total sealed soil. In general, the shares of Europe buildings built before 1975, between 1975 and 1990, between 1990 and 2000, and after 2000 are 40%, 26%, 12%, and 22%, respectively. The useful SH and SC demands for different types of buildings and different ages are based on Invert/EE-Lab database [37] and building typology [48]. It is commonly found that the buildings built before 1975 have at least 50% more demand for SH, compared to the buildings after 2000. Thereby, renovations on historical buildings were continuously proposed and conducted in European countries.

According to the report on energy renovations for European buildings during the period 2012–2016 [28], the renovation rates are classified into four categories, including the deep, medium, light, and below threshold renovations. The energy savings associated with the four categories are over 60%, between 30% and 60%, between 3% and 30%, and lower than 3%, respectively. The survey on renovation projects reflects that the annual floor areas of deep and medium renovations are only around 0.2% and 1% of the EU building stock, with small variations between countries. The total annual weighted energy saving rate was estimated close to 1% within EU. However, such progress is far behind if the EU want to achieve both its 2030 climate target and climate neutrality by 2050. Thereby, to reflect the future demand changes, two scenarios towards the year 2050 with different renovation plans were considered in this study. The main difference lies in the plans for deep and medium renovation measures, as generally introduced in Table 3. The light renovation measures are applied for buildings between 1990 and 2000 and are considered the same in two scenarios. As for the benefits of renovations, the SH demand saving potential level associated with each renovation measure is provided in the report by specific countries [28]. The country-level renovation rates were downscaled to all hectare-sized units inside. Besides, the renovation measures are assumed to have no influence on the SC, DHW, and process cooling demand. Therefore, considering the share of building ages for the hectare-level units, the specific renovation measures and the energy-saving benefits, the SH demand densities after renovations at year 2050 were calculated. The aggregated SH demand by building ages is shown in Fig. 3, with the moderate RCP2.6 climate scenario in 2050. Around 50% demand reduction is found in the fast renovation plan, which is close to the proposal to achieve carbon neutrality target [2,29].

Table 3
Two renovation scenarios and general plans for deep and medium renovation.

Name	Plans
Slow	Deep: current speed (~0.2%), on buildings before 1975 Medium: current speed (~1%), on buildings between 1975 and 1990
Fast	Deep: annual 1%, on buildings before 1990 Medium: 2 × current speed, on buildings between 1975 and 1990

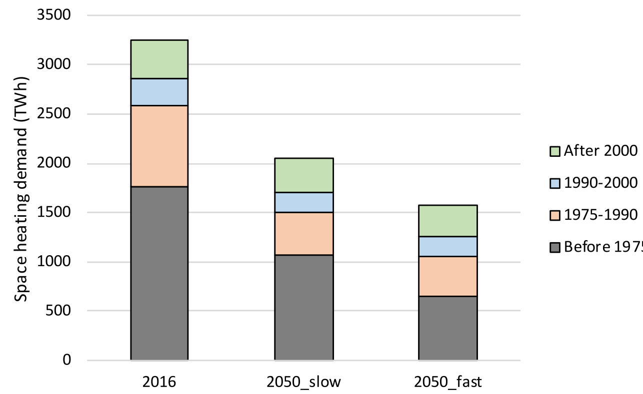

Fig. 3. Aggregated space heating demand by building ages for reference year (2016) and future (2050).

The results of future heating and cooling demand are further explained in Section 3.3.

According to the Hotmaps database, 12% of the EU building stock has space cooling, while the cooled area ratios for the residential and service sectors are 6.7% and 27.4%, respectively. Strong variations exist between countries due to the different climate and building characteristics. For Central and Northern European countries, less than 5% of the residential buildings have space cooling. While in Mediterranean countries, the cooled ratio is increased to more than 50%. However, influenced by the heatwaves and increasing requirement for comforting building environment during Summer, air-conditioners are growing fast in Europe. To reflect such changes in the future, the scenario that has doubled the cooled area than the reference condition is considered. For the service sector, since the cooled area ratio is already larger than 50% in some countries, the growth of SC is less significant than that in the residential sector. In general, 20% of the building stock has space cooling in the cooled area increase scenario. The planned cooled ratio on country level is downscaled to all hectare units inside. Then, the future SC demand density $Q_{SC,i}$ is generally calculated using Eq. (6).

$$Q_{SC,i} = GFA_i \times \varphi_{SC,i} \times q_{SC} \tag{6}$$

where $\varphi_{SC,i}$ is the downscaled cooled ratio for *i-th* hectare unit. q_{SC} is the unit area SC demand (kWh/m^2) for specific building tyles, derived from Invert/EE-Lab database [37] and building typology database [48]. Eq. (6) expresses the general method, while the specific calculation process is based on specific data for residential and service building types.

2.5. Overlapping demand

Previous sections have explained the methodologies for acquiring the annual demand quantity under various future scenarios. To get the temporal overlapping demand, the hourly demand profile is needed. In general, the hourly profiles are based on hourly temperature data and empirical demand profiles that reflect consumer behavior, acquired from the Hotmaps database [22]. For buildings with different functions and construction periods, identical hourly profiles are provided on the second levels of Nomenclature of Territorial Units for Statistics in Europe (NUTS-2). Then, these profiles are downscaled to the hectare-sized unit considering local building compositions.

For the SH and SC demand within specific day, the hourly structure is mainly dependent on the outside temperature and the local building characteristics. Then, to form the yearlong profile, daily profiles are aggregated considering the sequence of days in the year, the holiday activities, and average daily temperature. It shall be noted that the investigated SH and SC demand profiles are hypothetic, while the practical profiles are influenced by many factors such as the thermal inertia of the buildings and network. For DHW demand, empirical profiles based on field investigations in Germany building stock are applied. The demand profiles are further shifted in time to match the behaviors in other EU countries, based on the harmonized European time use survey [49]. For the process cooling demand, considering its use in the commercial refrigeration process, the profile is set the same for 8,760 h of the whole year.

Typical hourly profiles of heating and cooling demand along the whole year are presented in Fig. 4, using the example of a commercial district near Vienna, Austria. The cooling demand has a stable baseline from the process cooling part and a weather-induced SC part during summer. Similarly, the baseline of the heating demand comes from the DHW part while the variable demand is introduced by SH part. The overlapping demand is decided by the relatively smaller one between the heating and cooling demands, as calculated using Eq. (7). Although various demand-side management measures such thermal energy storage (TES) are effective in shifting demand, they are not considered in the analysis due to complex techno-economic issues associated with their applications. This limitation is further discussed in Section 4.

For every hectare-sized unit, the annual heating and cooling demand profiles are generated using above-mentioned methods, considering local weather conditions and building types. Then, the overlapping part is correspondingly calculated and the index DOC, which expresses the share of overlapping demand in the total demand, is calculated using Eq. (8). This index has been widely used to identify the economic attractiveness of the bi-directional 5GDHC system [12,16], and is considered as the main metric for evaluating the feasibility of 5GDHC.

The case study in Germany has proved that the 5GDHC system has lower supply cost than the reference individual solution when the DOC exceeds 0.45. The relationships between the DOC and energy system cost are further explored in [16]. Based on previous works, three levels of DOC, which are 0.2, 0.3, and 0.4, are considered for judging the feasibility of 5GDHC in Section 3.4. Based on the calculation results for all hectare-sized units, the locations fulfilling the DOC requirement are identified and plotted.

$$Q_{overlap} = \sum_{t=1}^{8760} \min\{P_{H,t}, P_{C,t}\} \tag{7}$$

$$DOC = \frac{2 \times Q_{overlap}}{Q_H + Q_C} \tag{8}$$

where $P_{H,t}$ and $P_{C,t}$ are the heating and cooling demand at hour t, respectively. The cumulative heating and cooling demand of a whole year are represented by Q_H and Q_C. $Q_{overlap}$ is the overlapping demand.

3. Results

The heating and cooling demand in 2016 is set as the reference scenario, considering the availability of most source data. The quantity of overlapping demand and its geographical distributions are explained in Section 3.1. The influence factors for the overlapping demand are analyzed and discussed in Section 3.2. Section 3.3 presents the changes in overlapping demand in the future due to climate warming and building stock changes. Considering the DOC criteria, the potential application areas for 5GDHC are also identified.

3.1 Reference scenario

The aggregated heating and cooling demand for the investigated European region is shown in Fig. 5. In total, the building stock has the GFA of 28,990 million m^2 and the entire demand of 4,081 TWh. The SH demand constitutes the major part while the SC and process cooling demand only consume 6.5% and 2.7%, respectively. The area demand indexes for the residential and service sectors are summarized in Table 4. Compared to residential buildings, the service buildings have larger unit area SC demand and smaller unit area DHW demand. It shall be noted that the overall demand is slightly larger than the previous heat roadmap assessment [4,5] for the EU building stock because the EFTA countries are included and the database year is moved from 2010 to 2016 in this work.

Based on the methodologies explained in Section 2.5, the

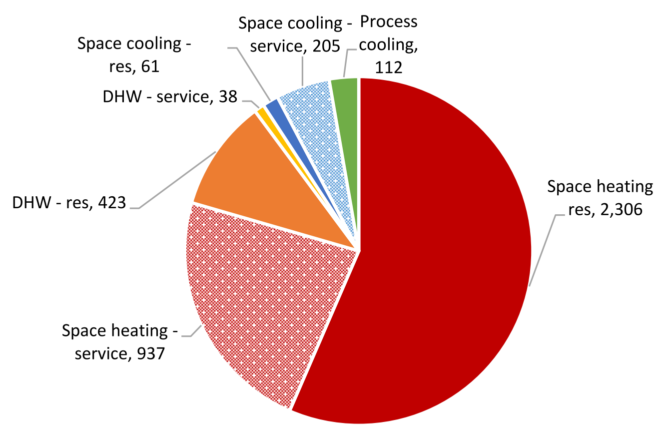

Fig. 5. The aggregated heating and cooling demand for the investigated region. Unit: TWh.

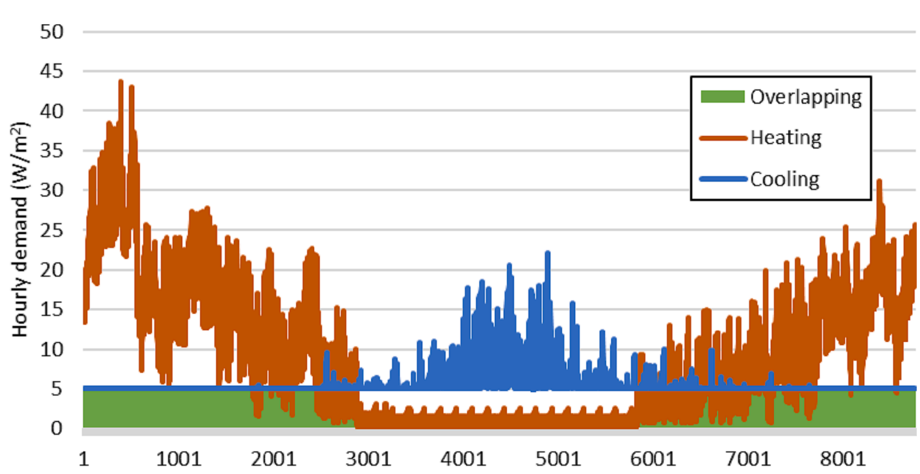

Fig. 4. A typical example of hourly heating and cooling demand along the whole year and the overlapping part.

Table 4
Aggregated floor area and area demand indexes for the residential and service sector.

	Floor area (million m^2)		Area demand (kWh/m^2)		
	Total	Cooled area	SH	DHW	SC
Residential	21,549	1,444	107	19.6	42.3
Service	7,441	2,039	126	5.1	100.5

overlapping heating and cooling demand was calculated for all hectare-sized units. To better present the results, the units are classified into different groups by DOC ranges and the share of floor area for each group is presented in Fig. 6. Most hectare units have DOC smaller than 0.1, meaning that they are almost inappropriate for the application of the 5GDHC system. Less than 0.1% of the building stock has DOC larger than 0.3, which is regarded as the threshold for the 5GDHC system being energy efficient in previous studies [12,16].

The comparison between two scenarios reveals that the process cooling can increase the overlapping demand and DOC index. This finding is explained from the structures of load profiles, as shown in Fig. 4. For most European countries, the SH demand exists in winter while the SC demand exists in summer. The overlapping part mostly comes from the relatively small DHW demand during summer, when the heating and cooling are needed at the same time. With process cooling demand throughout the whole year, especially during winter, more potentials for the simultaneously supply of heating and cooling exist. In accordance with previous works [17,18], the process cooling or the low-temperature waste heat is an important factor in the 5GDHC system. However, in terms of the practical European building stock, the overlapping demand is still relatively small. With process cooling, there are only around 14,000 ha units that have DOC larger than 0.4, taking up 0.03% of the total building area. Some of these units are located in rural area with small amount of heating and cooling demand. Considering the minimum demand density to support the district energy system [50] and the DOC index, the feasible locations of 5GDHC systems are geographically explained in Section 3.4. In total, the aggregated overlapping demand in the reference scenarios without and with process cooling are 118 TWh and 304 TWh, respectively.

The geographical distributions of DOC and overlapping demand in reference scenarios are presented in Fig. 7 and Fig. 8, respectively, using the Gothenburg area as an example. The city is located in the west coast of Sweden and is where the authors come from. Considering only the SC demand, the DOC in any place of the city is smaller than 0.1. With process cooling, a few areas have DOC larger than 0.2, which are mostly located in city centers or suburban satellite city centers. A commonality of these areas is the high share of commercial buildings, which require process cooling along the whole year. However, almost no hectare units have DOC larger than 0.3 because the heating demand is still dominant in Nordic countries. Concerning the overlapping demand as presented in Fig. 8, the units with large values are also in the city centers. The suburban areas with large DOC have relatively smaller demand density. Thereby, the two indexes DOC and demand density shall be combined for evaluating the 5GDHC potential, as further shown in Section 3.3.

In terms of the European building stock, due to the difficulty of directly showing over 20 million hectare-sized units, the area-weighted average DOC values for NUTS-2 regions are calculated and presented in Fig. 9, classified by different scenarios. Country-level aggregated results are presented in Supplementary Material. General trends are found from such figure while the specific potential areas with overlapping demand are presented in Section 3.3. It is clearly seen that from North to South, with warmer climate and higher cooling demand, the average DOC is gradually increased. The highest DOC values of around 0.2 exist in Mediterranean countries and Balkan countries. For the most middle and northern Europe countries, the average DOC values are smaller than 0.1. The analysis and discussions on different future scenarios are provided in Section 3.3.

3.2. Influence factors for overlapping demand

As is shown in Fig. 9, the DOC value increases with warmer climate. In this section, the specific influence factors for the overlapping demand are analyzed, based on results in reference scenarios. The cooling degree day (CDD) is used as the index to describe the climate conditions, and its relationships with the area weighted average DOC for NUTS-2 regions are presented in Fig. 10. As with the results in Fig. 9, strong relationship between climate and DOC is found. For the scenario with process cooling, less influence from the climate is found because the process cooling becomes the main contribution to overlapping demand. It is also clearly seen that with process cooling, the DOC index has been generally increased.

This study also evaluates the influence from other urban-planning factors using the Pearson correlation coefficient. To exclude the influence of weather, the correlation coefficients for the points within every NUTS2 regions were calculated separately. Then, the average values of all NUTS2 regions were calculated, as shown in Table 5. Since the process cooling demand originates from the commercial refrigeration

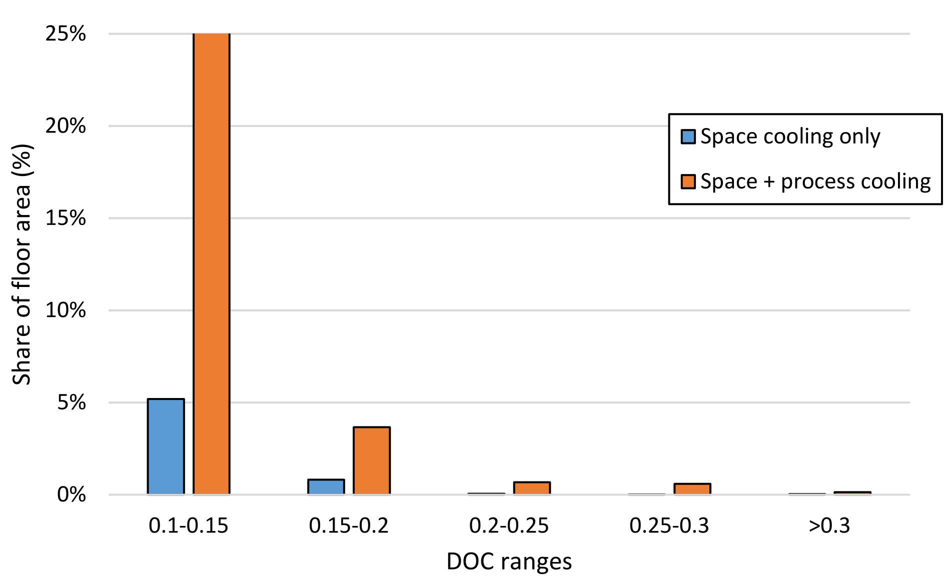

Fig. 6. DOC ranges and the corresponding building area shares in the whole studied European region.

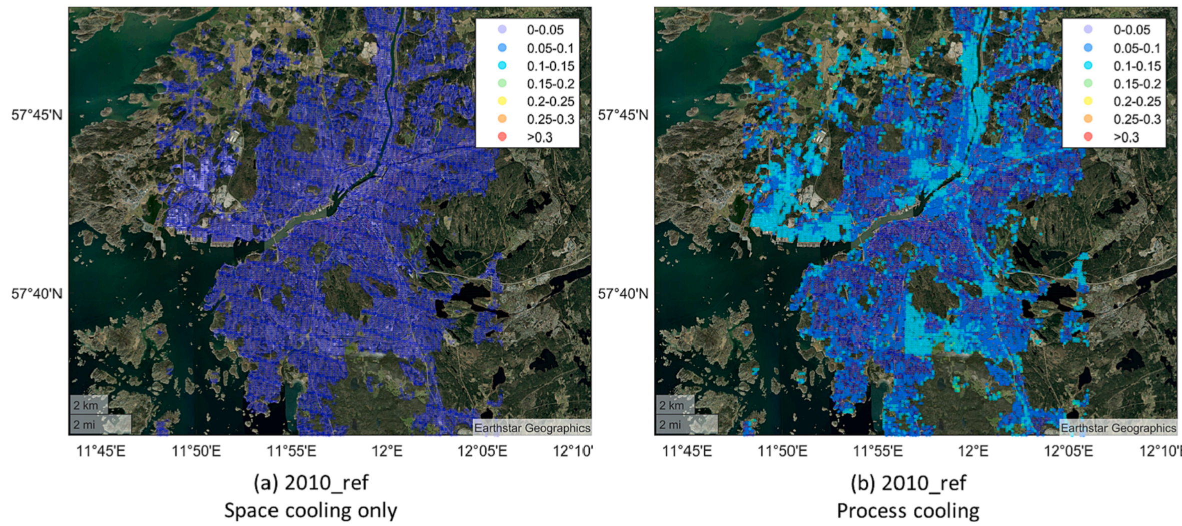

Fig. 7. DOC in the Gothenburg area.

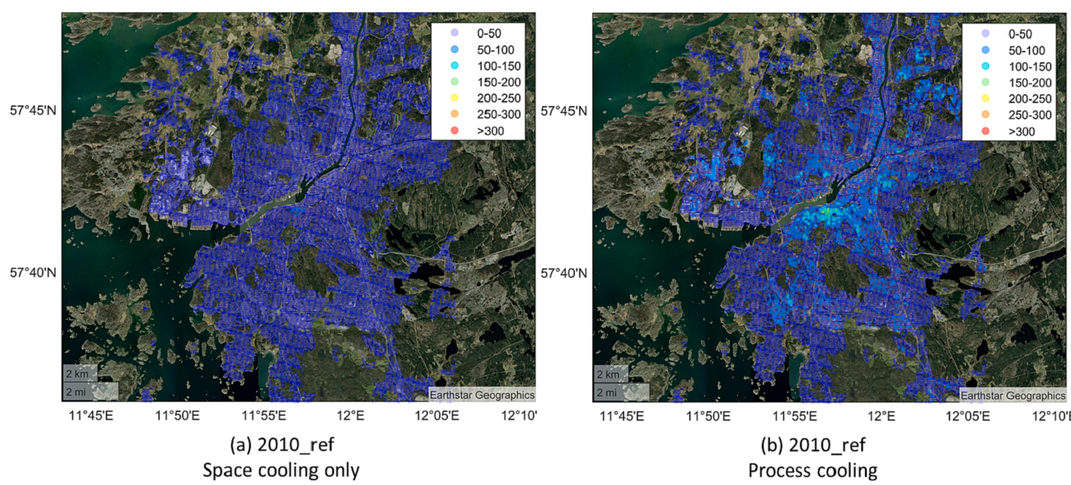

Fig. 8. Overlapping demand in the Gothenburg area. Unit: MWh/hm^2.

process, the ratio of service buildings has strong relationship with the DOC. However, for the scenario with only SC demand, the overlapping part mainly comes from the DHW demand during summer. As shown in Table 4, the service buildings have less DHW demand than the residential buildings. Thereby, the ratio of service building is negatively contributing to the DOC. The results also revealed the insignificant influence from floor area density and demand density to the DOC. This means that high DOC values could also exist in the suburban area, as shown in the city example in Fig. 7. Thereby, it is important to consider both the demand density and DOC to identify the feasibility of 5GDHC, as further discussed in Section 3.4.

3.3. Overlapping demand in the future

With the changes summarized in Table 2, the future heating and cooling demands were analyzed and shown in Fig. 11. It is seen that building renovation has much more influence on the demand than the climate change, in accordance with previous works [16]. Around 50% of SH demand is reduced by fast renovation plan, which is considered as the necessary step from national energy planning studies to achieve carbon neutrality target [24,30]. At the same time, the SC demand will undergo drastic changes from warmer climate and growing cooling area. The share of SC demand gradually increases from less than 10% to around 20% by climate change. In scenarios with cooling area increase, this value can even reach 30%, meaning that the SC will surpass DHW as the second largest demand. It is unequivocal that the roles of SC, DHW and process cooling demands will become as important as SH demand in the future.

The warmer climate also influences the length of the heating and cooling period. As mentioned in Section 2.1, the average lengths of SH and SC period within the entire study region in reference scenario are 4,800 h and 1,900 h, respectively. In year 2050, the average SH period is reduced by around 100 h while the average SC period is increased by 200 h. In general, more occasions of simultaneous heating and cooling demand will exist.

Given the changing heating and cooling demand, the overlapping demand in future scenarios is presented in Fig. 12, classified by DOC ranges and the shares of floor area. Despite the drastic changes found in the SH and SC demand alone, the majority of the building stock still has DOC lower than 0.2, which is considered as infeasible for 5GDHC. Thereby, the figure focuses on the area that have DOC larger than 0.2 as potential places for the bi-directional 5GDHC. From the aggregated demand presented in Table 6, it is seen that the future climate changes and renovations have little impact on the true values of overlapping demand. This finding is in line with the demand structures explained in Section 3.1, that the changes in SH and SC mostly exist in two separate

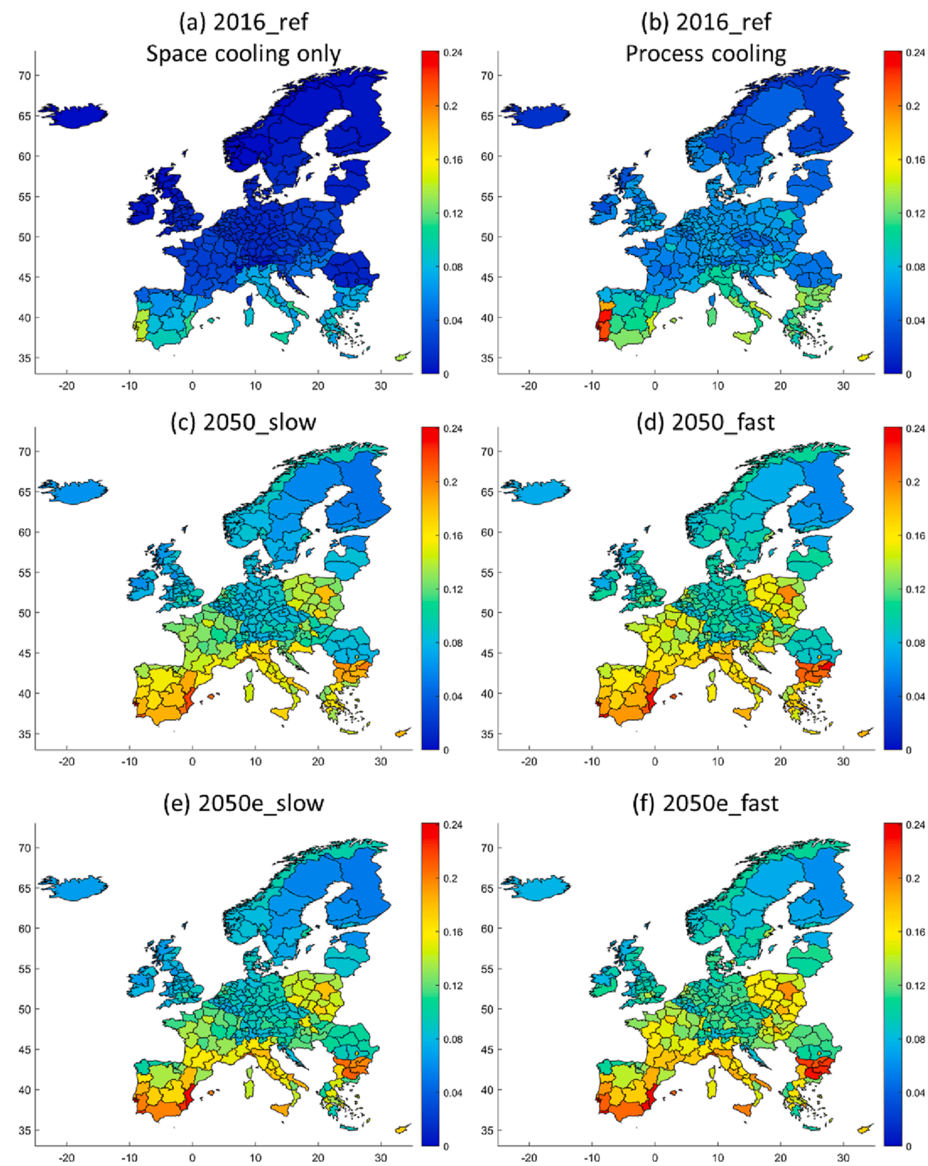

Fig. 9. Area weighted average DOC for NUTS-2 regions in different scenarios.

time periods. Thereby, the overlapping demand is mainly influenced by the process cooling, which has demand over the whole year and has potential to be supplied simultaneously with other demands.

From another perspective, with the reduction of total demand, the share of overlapping demand is increased in the future, as presented in Table 6. The share of area that have DOC larger than 0.2, has the maximum value of 12.2% at scenario with fast renovation plan and current cooling area. Similar with the trend in Fig. 11, building renovation has more impact than the climate change. However, most changes are referred to the DOC range between 0.2 and 0.25. The area that has DOC larger than 0.3, which is the threshold for 5GDHC being energy efficient, still has less than 1% in the entire building stock. If considering the DOC larger than 0.4, the share of floor area is between 0.1% and 0.2%. Quantifications of these area and the geographical distributions are presented in Section 3.4, as potential applications of 5GDHC.

As for the possible increase of cooling area in the future, the overlapping demand is indeed increased by around 20 TWh, compared to scenarios with cooling area unchanged. However, such increase is only a small part in the overall increased SC demand, which is between 200 and 300 TWh. The finding again proves that the overlapping demand is less influenced by the changes in SH and SC demand. Besides, the change of cooling area increases the total demand, which instead lowers down the share of overlapping demand, as shown in Fig. 12. The share of floor area with DOC larger than 0.2 is decreased compared to scenarios with no cooling area changes.

The area weighted average DOC for NUTS-2 regions in future scenarios are shown in Fig. 9. Compared to reference scenarios, DOC values are generally increased in the future. The change is much more visible in Mediterranean countries, where the average DOC becomes larger than 0.16. For middle and northern European countries, the average DOC is around 0.1. The geographical distribution of DOC also proves the influence of weather conditions. However, the regional average values only represent the general trend, while the detailed distributions of potential areas for 5GDHC are explained in the following Section 3.4.

3.4. Potential areas for 5GDHC system

To identify the potential application areas of 5GDHC system from all investigated hectare-sized units, three selection rules based on DOC and demand density values are set in this study, as presented in Table 7. The DOC criteria of 0.2 is considered as the lower limit for 5GDHC

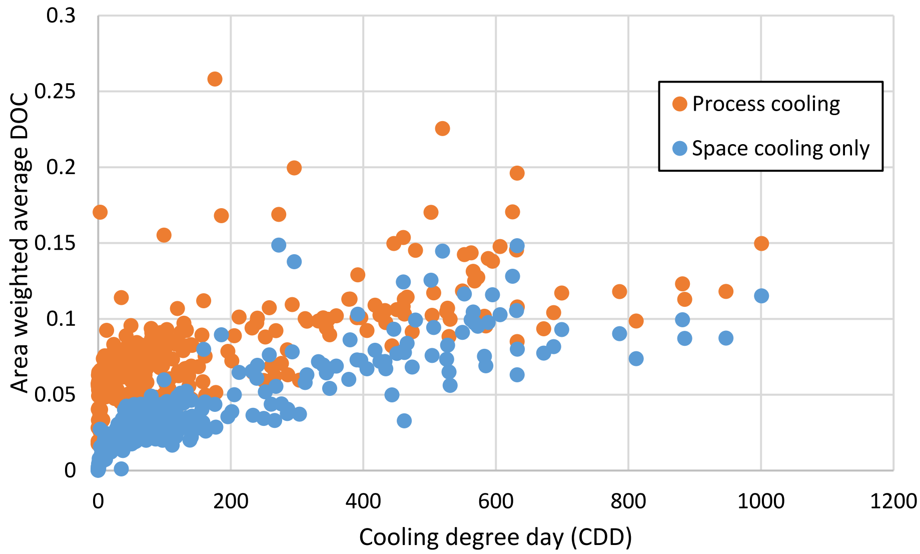

Fig. 10. Relationships between the cooling degree day (CDD) and area weighted average DOC for NUTS-2 regions.

Table 5
Correlation coefficients between different geographical indexes and the DOC.

	CDD	Service building ratio	Floor area density	Demand density
Space cooling only	0.84	−0.75	0.21	0.17
Process cooling	0.66	0.78	−0.28	−0.29

application, while the value of 0.3 is assumed as the point when 5GDHC is energy efficient [12]. As for judging the general feasibility of district system, various indexes such as linear demand density [51] and plot ratio [52] were used in previous works. It is known that the DHC system is more attractive than individual solutions in places with large floor area and high demand density. Thereby, two levels of total demand density were directly used as criteria in this study. Considering an average area demand index of 120 kWh/m^2 in Europe, the two demand densities correspond to the plot ratios of 0.42 and 0.25, respectively. According to practices from city planning, these two levels represent the building area densities in inner-city area and suburban area.

Based on the three rules, the units meeting the requirement are selected and summarized in Table 8. The reference scenario with process cooling and future scenarios with slow and fast renovation plans are considered. From the entrance threshold of rule 1 to stricter requirement of rule 2, the number of available units and corresponding floor area are significantly reduced. Indeed, for the fast renovation scenario that has the largest overlapping demand, only around 2500 ha-sized units are identified as potential areas for 5GDHC application. With less stringent requirement for demand density in rule 3, the potential number of units is slightly increased compared to rule 2, meaning that more suburban area is included. However, compared to the entire building stock with a total floor area of 28,990 million m^2, the potential area of 5GDHC takes only a small share. Besides, although there are tens of thousands of hectare units with DOC larger than 0.4, almost none of them satisfy the demand density criteria. They are mostly located in rural area with small demand and, thereby, not suitable for 5GDHC system. The results also reveal the huge differences between renovation patterns, as with the findings from Fig. 12. In regions with more ambitious renovation plans, more focuses shall be paid when planning the 5GDHC systems.

The geographical distributions of potential units are shown in Fig. 13. It is seen that with rule 1, the selected units cover the major metropolitan areas of Europe. However, less units from southern European countries were identified with stricter requirement for DOC in rule

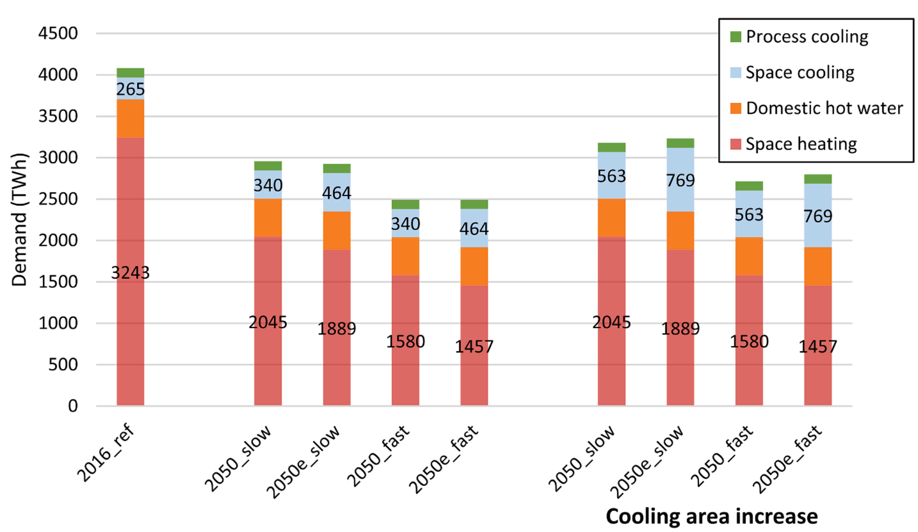

Fig. 11. Distributions of heating and cooling demand in future scenarios.

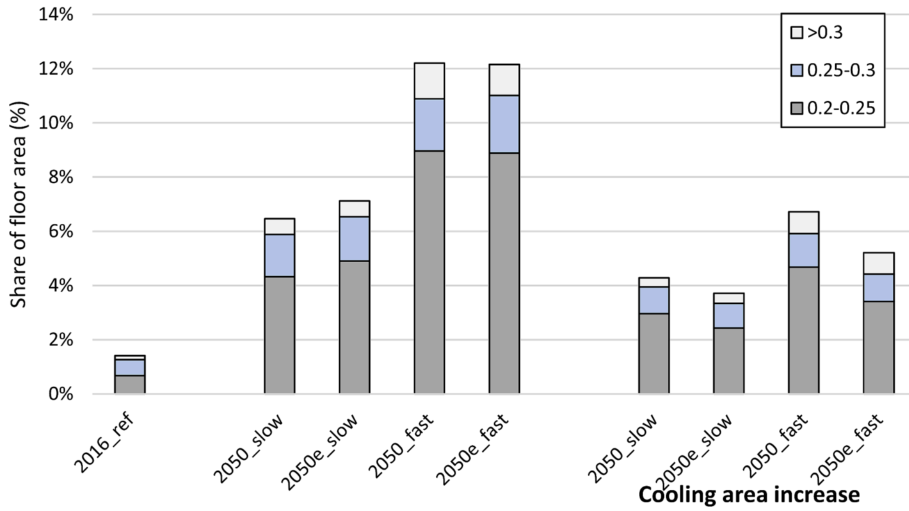

Fig. 12. DOC ranges and the corresponding shares of building area in the whole studied European region.

Table 6
Overlapping demand in future scenarios and its share in the total heating and cooling demand.

Scenarios		Overlapping demand (TWh)	
2016 reference	SC only	118.4	3.0%
	Process cooling	303.9	7.4%
Cooling area same	2050_slow	325.8	11.0%
	2050e_slow	329.2	11.3%
	2050_fast	325.0	13.1%
	2050e_fast	329.0	13.2%
Cooling area increase	2050_slow	348.5	11.0%
	2050e_slow	346.9	10.7%
	2050_fast	347.0	12.8%
	2050e_fast	346.6	12.4%

Table 7
Rules of identifying the potential areas for 5GDHC system application.

	DOC	Demand density
Rule 1	>0.2	>500 MWh/hm^2
Rule 2	>0.3	>500 MWh/hm^2
Rule 3	>0.3	>300 MWh/hm^2

Table 8
The aggregated floor area and total demand of hectare-sized units meeting selection rules 1–3, under slow and fast renovation scenarios.

Rule	Scenarios	Number	Floor area (million m^2)	Total demand (TWh)
Rule 1	2016_ref	2702	24.5	1.7
	2050_slow	29,678	304.6	22.5
	2050_fast	84,485	890.7	68.2
Rule 2	2016_ref	51	0.6	0.03
	2050_slow	428	3.9	0.3
	2050_fast	2598	24.9	1.7
Rule 3	2016_ref	408	3.1	0.2
	2050_slow	2048	12.6	0.9
	2050_fast	10,204	66.4	4.6

2. This is due to the structure of heating and cooling demand in the future. In the urban centers of warmer climate regions, the cooling demand is already the dominant sector. The reduction of SH demand from assumed future changes cannot further improve the DOC value. By contrast, in mid-European countries, the reduction of SH and the increase of SC makes the quantities of two demand closer to each other. From the perspective of supplying the heating and cooling simultaneously, these mid-European regions are more suitable than the southern regions.

4. Discussion

This study has explored the overlapping heating and cooling demand in Europe and identified the potential areas for the applications of the 5GDHC system. In the evaluation process, the demand profiles are based on empirical data, while active demand-shifting measures such as thermal energy storage (TES) are not considered. Indeed, in addition to the demand-side management benefits that have been widely acknowledged [53], TES unit can also effectively improve the balance of heating and cooling in 5GDHC system [16]. By considering the current DOC and heating to cooling ratio, the maximum overlapping potentials can be theoretically analyzed, which are the potentials for TES application. Both long-term seasonal TES and short-term diurnal TES are applicable for matching the heating and cooling demand. Moreover, by considering the initial investment and cost that are highly proportional to the TES size, the economic optimal applications of TES can be acquired across geographical regions. Thereby, the inclusion of TES in the spatial planning of 5GDHC is a promising direction that requires further works.

It shall be noted that the methodologies and results in this study can only be used for top-level planning and analysis for regional trends. For detailed design of the 5GDHC system on specific cases, bottom-level information such as building characteristics are needed. Besides, despite the important role of the process cooling in the 5GDHC system, it is hard to provide convincing data on its potential from bottom-level. Thereby, this study has used empirical values from various building typologies [41,42]. It is possible that a special commercial area has different process cooling demand and thus the overlapping potential is improperly assessed. However, the analyzed process cooling demand has been cross-checked with the aggregated demand on country-level, making sure that the results are convincing from a general view. Besides, the spatial and temporal evaluation methodology of this study can be applied in a specific region by including local details such as the quantity of process cooling demand. The method is still effective in finding feasible areas for 5GDHC, which bridges the bottom-level KPIs and top-level planning.

The DOC index and demand density are selected as two criteria for evaluating the feasibility of 5GDHC. It shall be noted that there are also other factors influencing the application, such as the equipment price and availability of natural cooling sources, as pointed out in recent sensitivity analysis studies [17]. The general pre-requisites of the

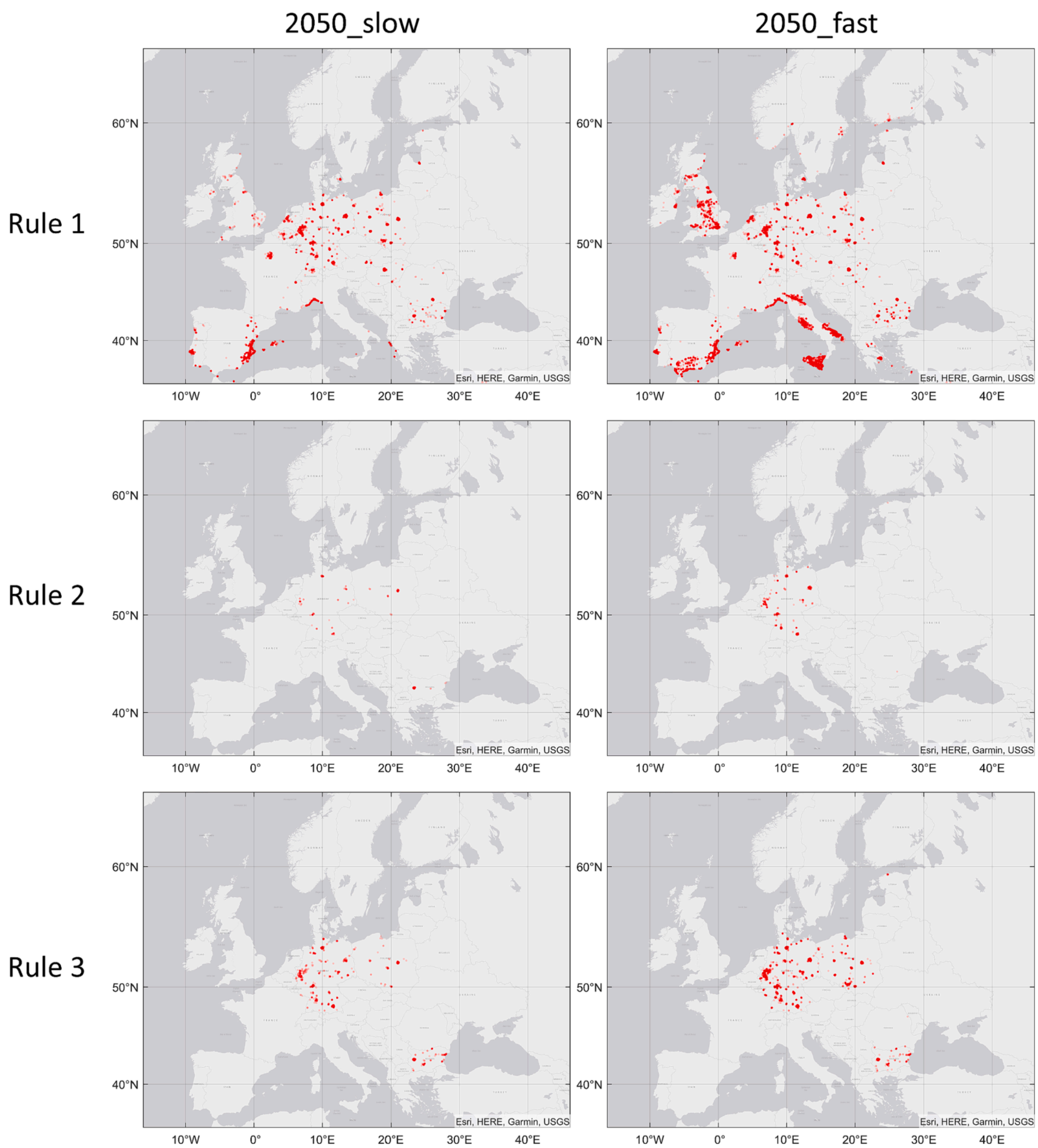

Fig. 13. Geographical distributions of hectare-sized units meeting selection rules 1–3, under slow and fast renovation scenarios.

5GDHC system have been identified in this work. It is also interesting to combine the geographical characteristics of other influencing factors to increase the reliability of the results.

5. Conclusion

This study aims to evaluate the application potential of the 5GDHC system in the entire European building stock, using database containing the geographical information of hectare-sized units. The overlapping heating and cooling demand and the demand densities are calculated and applied as criteria for judging the 5GDHC feasibility. Moreover, considering the future possible changes on demand due to warmer climate, building renovations, and cooling area increase, this study investigated 8 future scenarios and the changes on the overlapping demand and potentials of 5GDHC. Key conclusions are summarized as follows:

1) In the reference scenarios that represent the building stock of year 2016, most hectare units have DOC smaller than 0.1, meaning that they are almost inappropriate for the application of the 5GDHC system. Less than 0.1% of the building stock has DOC larger than 0.3, which is the threshold for 5GDHC being energy efficient.

2) Due to its demand structures, process cooling is proved to increase the overlapping demand, and is thereby regarded as a key factor in the 5GDHC system. In reference scenarios, high DOC values are found in warmer climate regions with high ratios of service buildings, such as the commercial centers in Southern European countries.

3) Despite the reduction of SH demand and increase of SC demand in the future, the practical overlapping demand is only slightly increased by 5%. The main reason is that the changes in SH and SC mostly exist in two separate time periods. As the overall demand is reduced by around 40% in the future, the DOC values are generally improved. However, the area that has DOC larger than 0.3 and 0.4, still shares only around 1% and 0.1% respectively, of the entire building stock.

4) The potential areas for the 5GDHC system under future scenarios are statistically counted up and geographically presented, based on two criteria including the DOC and demand density. In the most stringent rule that required DOC larger 0.3 and demand density larger than 500 MWh/hm^2, only around 2500 ha units are identified.

CRediT authorship contribution statement

Yichi Zhang: Methodology, Validation, Investigation, Formal analysis, Writing – original draft. **Pär Johansson:** Conceptualization, Writing – review & editing, Supervision. **Angela Sasic Kalagasidis:** Conceptualization, Resources, Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Angela Sasic Kalagasidis reports financial support was provided by Swedish Research Council Formas.

Data availability

The data that has been used is confidential.

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Appendix A. Supplementary data

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