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From waste to heat: A spatio-temporal analysis of the surplus heat potential for Denmark's district heating systems

Marina Georgati [1], Poul Alberg Østergaard [2], Steffen Nielsen [2], and Carsten Keßler [1,3]

[1]Department of Sustainability and Planning, Aalborg University, Copenhagen, Denmark
[2]Department of Sustainability and Planning, Aalborg University, Aalborg, Denmark
[3]Department of Geodesy, Bochum University of Applied Sciences, Bochum, Germany

Correspondence: Marina Georgati (marinag@plan.aau.dk)

Abstract. Unused energy is released into the environment from a number of sources, such as energy-intensive industries, whereas it could be used in district heating (DH) systems to make a significant contribution to decarbonising the heating sector. Despite its essential role, surplus heat (SH) is currently under-utilised and large amounts are wasted. Furthermore, there is a lack of detailed data in the literature on the sources that could potentially be captured. This paper examines the historical distribution of DH systems and their relationship with SH in Denmark, a country with very advanced DH. It also considers the potential for medium and low-temperature sources to be included alongside high-temperature industrial SH, which has been the dominant resource to date. Specifically, it utilises visual and statistical interpretation of the geospatial distribution of the utilised amounts of SH at municipal level. The analysis shows through classified choropleth mapping the dynamic temporal and spatial changes in the field, where the potentials depend on the availability of sources and their corresponding activities, but also shows that many municipalities with high and increasing DH shares could utilise SH from various sources that are not currently used such as in the food and beverages and retail and trade sector. Further potential from manufacturing and industrial activities could also be included, especially in the municipalities of the capital region, while significant low-temperature SH across the country would require a boost from heat pumps or upgrading of DH systems.

Submission Type. Analysis, case study

BoK Concepts. [AM1-2] Analytical approaches; [TA11-2] Users in energy and mineral resources; [TA11-3-2] Users in utilities & supplies

Keywords. spatiotemporal mapping, decarbonisation, energy planning, heat sources, excess heat

1 Introduction

District heating (DH) is a system designed to use local energy resources to meet the heating needs of consumers (Frederiksen and Werner, 2013). The thermal energy supplied to the system typically originates from combined heat and power (CHP) plants, waste-to-energy (WtE) facilities, boilers, and surplus heat (SH) from industrial activities (Werner, 2017; Frederiksen and Werner, 2013). Recently, the integration of renewable energy sources, such as geothermal, solar thermal, biomass and ambient heat through heat pumps has further enhanced the sustainability of DH systems. By combining heat recycling and renewable energy, DH systems reduce the dependency on fossil fuels, increase energy security and offer significant environmental and economic benefits.

Denmark has one of the most advanced and widespread DH systems in the world supplying space heating and domestic hot water to two thirds of the private households (Johansen and Werner, 2022). In 2024, 57.2% of the heated floor area relied on DH (Danmarks Statistik, 2024). Danish DH systems draw from diverse heat sources, including CHP plants, heat pumps, fuel boilers, electric boilers, geothermal energy, solar collectors and SH recovered from industrial or commercial activities. In some places, exploitation of heat from power generation could also be considered SH, however in Denmark CHP is so engrained in the system and has been a motivating force for the establishment of CHP that the term surplus would not be appropriate in this context.

Despite its key contribution to national energy transition goals, SH in Denmark accounted for only 4% of the total DH production in 2022 (Energistyrelsen, 2023). Specifically, the Danish Energy Agency (DEA) reported 64 SH suppliers connected to 39 Danish DH networks. In most cases, the suppliers contributed more than 10% of the total heat supply (Energistyrelsen, 2023). However, the DH levels are not evenly distributed geographically across the country, nor is the use of SH. While specific DH systems, such as those of Agersted, Fensmark, and Nederby-Debel, cover a significant part of the heat supply with SH (85-97%), the majority of the approximately 400 Danish DH systems do not significantly utilise this potential resource (Energistyrelsen, 2023).

This current under-utilisation may be attributed to various factors, with the unavailability of SH sources producing heat at sufficiently high temperature levels (70 to 120°C; Mazhar et al., 2018) in proximity to DH systems being a key constraint. Limited awareness and economic profitability challenges may also play a role. Investment uncertainty of DH companies has also been a persistent issue, influenced by factors such as taxation policies, the lack of a regulatory framework until 2018 (Johansen and Werner, 2022), and the recently abolished price cap on SH (Vejrup, 2024; Ritzau, 2025). Nevertheless, emerging opportunities — such as the use of waste heat from data centres — highlight the potential for SH to play an increasing role in Denmark's sustainable energy transition.

This paper analyses the historical spatial distribution of DH systems and their connection to SH in Denmark by employing choropleth mapping. It also considers the potential for incorporating medium- and low-temperature sources alongside high-temperature industrial SH, which has been the dominant resource to date. As fourth generation DH systems emerge, these allow utilising heat resources at lower temperature levels (50-60°C; Lund et al., 2018).

2 Background and related work

The ability for DH systems to tap into SH sources varies according to geographical location, proximity to respective infrastructure and economic characteristics of areas. For this reason, a spatial assessment of the location and capacity of SH sources and heat demand in proximity is necessary. Several studies have already explored the potential for matching SH to the location of modelled heat demand and DH areas at different geographical scales (Persson et al., 2014; Manz et al., 2021; McKenna and Norman, 2010; Chambers et al., 2020; Bühler et al., 2017; Doračić et al., 2018; Dou et al., 2018; Nielsen et al., 2020). Most studies have prioritised excess heat recovery from industrial processes, focusing on quantifying the potential at high temperatures. That focus is primarily due to the higher efficiency of high-temperature heat, which can be integrated directly into third-generation DH systems – the technology on which most existing networks are based.

When lower temperature SH is used in such systems, electric heat pumps are often required to raise the temperature to the necessary levels. However, the development of fourth generation DH technologies, which operate at lower grid temperatures and with reduced losses, now allows the direct integration of medium and low temperature SH without the need of heat pumps, as examined by other studies (Manz et al., 2024; Loibl et al., 2017; Moreno et al., 2024).

A recurring problem in the above studies is the lack of a robust database detailing the amount and location of SH. For example, Persson et al. (2014) estimates heat volumes based on current CO_2 emissions, while others rely on literature reviews (Miró et al., 2015). In contrast, more recent research on Denmark has used facility data from the Danish Central Business Register (Moreno et al., 2024). In addition, many of these studies use modelled data on heat demand in DH areas derived from building stock simulations. These data often differ from actual heat production and consumption patterns. As a result, there is a significant knowledge gap regarding the extent to which SH is currently being integrated into DH systems at subnational and local levels, and where additional efforts could improve the integration of further SH into these systems. By mapping the past extent and current potential of SH in the Danish DH systems, this paper contributes to filling this gap.

While these studies may not be published in geospatial journals, they incorporate GIS-based analyses and methodologies that are highly relevant to this research. They build on key spatial concepts such as feature proximity, spatial correlation (between SH sources and urban/rural areas; Persson et al., 2014) and spatial clustering (Chambers et al., 2020; Manz et al., 2024). These concepts play a crucial role in energy planning, and as their methodologies could be further developed in the geospatial sciences, this paper aims to highlight an area where geoinformatics has not yet been widely applied.

3 Data and methods

Methodologically, the analysis focuses on the visual and statistical interpretation of SH utilisation in the Danish DH systems, both historically and in terms of future potentials. The following sections outline the methodological approach for the two parts of the study, the data and processing steps.

To analyse the spatial and temporal distribution of SH use, we used classified choropleth mapping (Andrienko and Andrienko., 2006) to express the proportion of heat production in DH systems recovered from SH during the selected years. Several studies have already demonstrated the effectiveness of choropleth maps in conveying spatio-temporal patterns and have highlighted caveats related to spatial units and scale, attribute values, classification methods but also the readability and interpretation of the map (Schiewe, 2023; Juergens, 2020; Cybulski, 2022). For this reason, it was important in this study that the visual representations strike a balance between sufficient detail and excessive complexity or oversimplification, allowing consistent interpretation across decades and highlighting meaningful variations and distinctive features of the distribution of the utilisation levels (Andrienko and Andrienko., 2006). Five classes were manually defined in a colour scheme of yellow-red-blue gradients allowing for the comparison of municipal patterns over time, while maintaining the clarity of large changes and relevance of variance of class boundaries. The classes were defined taking into account the national averages and the distribution of the values over time, highlighting municipalities with the highest levels of utilisation and corresponding SH potential, but also temporal changes.

Due to several reasons, including the development and expansion of DH areas over the past decades, while municipal boundaries have remained relatively unchanged and to improve the readability of the maps, this study presents results at municipal level. It categorises the use of SH into high (above 80°C), medium (60-80°C) and low (below 60°C) temperature levels, when applicable. It is important to clarify the spatial relationship between DH areas and municipalities – a single DH area might extend over several municipalities, while a municipality may contain more than one DH area. However, the heat production plants supplying a DH area are located within a single municipality.

Five heat recovery sectors are analysed: agriculture, forestry and fishing; energy, mining and services; food and beverage; manufacturing and industry; retail and trade.

3.1 Current and past SH utilisation

The historical data on the recovery of SH in the Danish DH systems derive from the Energy Producer Census (EPT; Energistyrelsen, 2024a) – collected by the DEA for energy statistics. The census contains information on SH suppliers, which are defined as '*plants*' that supply SH (e.g., an oil refinery, a slaughterhouse). The EPT contains information on heat production, which DH network the plant supplies heat to and in which municipality the plant is located. For the analysis, we selected facility units under the category '*fuel free*' and '*commercial plant*', including those supported by heat pumps, but excluding SH from CHP plants. The dataset covers the years between 1994 and 2022.

Since the dataset already contains the information at the municipal level, we aggregated the heat production and estimated the corresponding contribution shares relative to the total annual DH production. The geospatial layer containing municipal boundaries (Klimadatastyrelsen, b), was then used to join to the aggregated shares forming the basis for statistical analysis, visualisations and maps. We selected four reference years – 1994, 2002, 2012 and 2022 – to provide a representative overview of long-term trends in SH while keeping the dataset manageable. 1994 and 2022 were the earliest and latest years in the dataset, reflecting the respective states of the sector, so ten-year intervals were chosen to capture key developments over time. This approach allows us to track both the persistence of key SH suppliers and the emergence of new ones.

Although the above EPT dataset is not openly available, a subset covering the years 2021-2023 is publicly available (Energistyrelsen, 2024b). This subset contains information on the specific companies providing SH to the respective DH systems. This dataset was used to estimate the contribution of SH by sector and municipality. The classification of companies into the above sectors was done manually through an extensive review of publicly available information, including company websites and industry classifications.

3.2 Technical potentials

To estimate the achievable potentials, we utilised the dataset provided by Nielsen et al. (2022), that maps heat sources by sector and temperature levels (Mathiesen et al., 2021; Moreno et al., 2024). As the sectors in the dataset are very detailed, they were reclassified into the selected sectors for analysis. Proximity to DH systems is important for reducing losses. We therefore considered only those sources that overlap with existing DH areas – referred to as *technical potentials*. This approach thus excludes sources outside the reach of DH systems, giving a more technically feasible estimation. It also provides a conservative assessment as sources in the vicinity of DH systems are not included. The vector layer of the DH areas, openly provided by Klimadatastyrelsen (a), was used to intersect with the point sources. To compare the size of the heat potentials obtained, we used the 2022 DH production levels as a reference.

3.3 Data and software availability

All data processing and visualisation was done in Python - the repository is available on GitHub (https://github.com/mgeorgati/surplusheatDK). Links to all publicly available datasets are provided above and included in the repository. The historical EPT data on past SH use was obtained from the DEA by special request and is not publicly available.

4 Results and discussion

This section presents the preliminary results obtained, starting from observations at national level and elaborating onto municipal level. It also discusses the results by sector in relation to other studies.

Historically, the national share of excess heat in the total DH system has fluctuated slightly over the years, generally ranging between 1.6% and 4%. From 1994 to 2009, it remained stable at around 2.2% before dropping to its lowest level in 2010 – the year with the largest amount of produced heat in the 28-year examined period. As Figure 1 shows, in 2010, a year with a particularly cold winter, the lowest amount of SH was used along with a reduction in the number of units connected to the DH network. The use of SH, together with the number of connected units, started

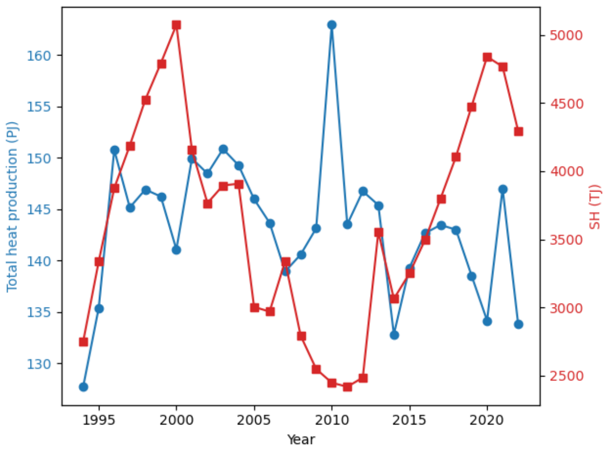

Figure 1. This line graph shows the annual national DH production in blue and the amount of SH utilised in red in the examined period.

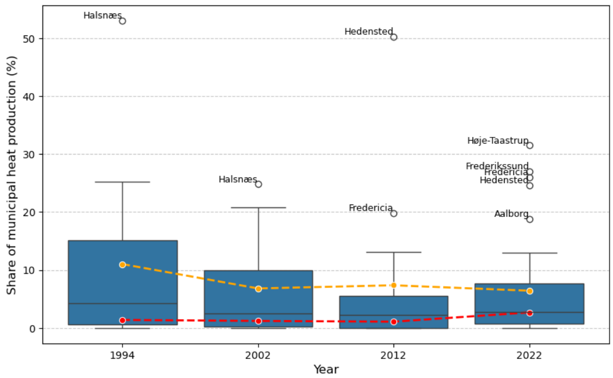

Figure 2. This box-plot displays the share of total heat production from SH across municipalities in 1994, 2002, 2012, and 2022. The boxes represent only municipalities that utilize SH, while the red dashed line shows the national average, which includes all municipalities—including those that do not use SH at all. Outliers are labelled with municipality names.

to increase in 2013, reaching 3.5% in 2020, but decreased slightly in 2021 and 2022 to 3.17% – potentially affected by the impact of the Covid-19 pandemic when industrial activity decreased. In 2019, SH with temperature boosting through heat pumps started being utilised covering 0.82% of DH production in 2022, showing that lower temperature SH has recently started being integrated into DH systems. The initial decrease in use between 2006 and 2013 can be attributed to the effects of the financial crisis, which affected industrial activity or led to its relocation. Similarly, the decrease observed in 2021 may be linked to the energy crisis, during which natural gas prices increased. However, further research is needed to confirm these relationships, which are beyond the scope of this study.

Focusing on the utilisation of SH at municipality level, Figure 2 and 3 map the contribution of SH in the DH production across the Danish municipalities in the examined years. The utilisation of SH reaches high levels in certain municipalities and years, but in most of the municipalities it remains below 5% with a high number of municipalities and their corresponding DH systems not utilising SH at all. This variation is represented by the difference between the orange and red lines of Figure 2, where in the first case the average is estimated only for the municipalities that use SH, while in the second all municipalities are considered. The average share for the municipalities actually using SH is at 11%, 6.81%, 7.35%, 6.41%, respectively, for the examined years.

The municipalities where a continuous utilisation of SH ranges at high levels are Fredericia with a refinery contributing to 15-26% of the DH production, in Aalborg with its cement industry and Hedensted with industry handling organic by-products. Several DH systems in municipalities have more recently started increasing the exploitation of SH from the available resources, such as Frederikssund, Mariagerfjord, Ringkøbing-Skærn, Billund, Morsø, Ballerup, Næstved, Nyborg. On the other hand, the utilisation of SH has been reduced in the DH systems of Faxe, Thisted and Brønderslev. The municipalities using SH with heat pumps are located in the capital region, Fyn, and mid-Jutland (e.g. Horsens, Favrskov, Hedensted).

In terms of additional resources for the DH systems, Figure 4 illustrates the total technical potentials that could be acquired. In most municipalities, the potential for using SH exceeds current levels. This is particularly evident in the Capital Region of Copenhagen, where significant high and medium temperature potentials are identified in Ballerup, Høje-Tåstrup, Tårnby and Gladsaxe, as well as in Kerteminde on Funen. Additionally, higher shares of low temperature SH are observed in municipalities where high- and medium- temperature SH are also observed, with concentrations mainly in central and southern Jutland.

Examining the specific sectors contributing to SH, the largest current contributors are energy, and services, and manufacturing and industry, as shown in Figure 5. However, the given dataset of SH potentials suggests that the manufacturing and industry sectors could play an even more significant role in the future. At the same time, the food and beverage industry also emerges as a significant untapped source of SH.

Comparing these findings with previous studies by Manz et al. (2021) and Bühler et al. (2017), which estimated SH potentials of 638GWh and 1,360GWh – corresponding to 1.73% and 3.69% of Danish DH production in 2022 respectively – our results indicate that the 2022 national SH share of 4% could be increased by an additional 2.6% from high and medium temperature SH and by 6.7% from low temperature SH.

The analysis of the past data shows the variability and uncertainty of SH use, as it depends on the availability and operational status of heat-producing sources. While SH has the potential to contribute significantly to the decarbonisation of DH, the majority of heat supply will still

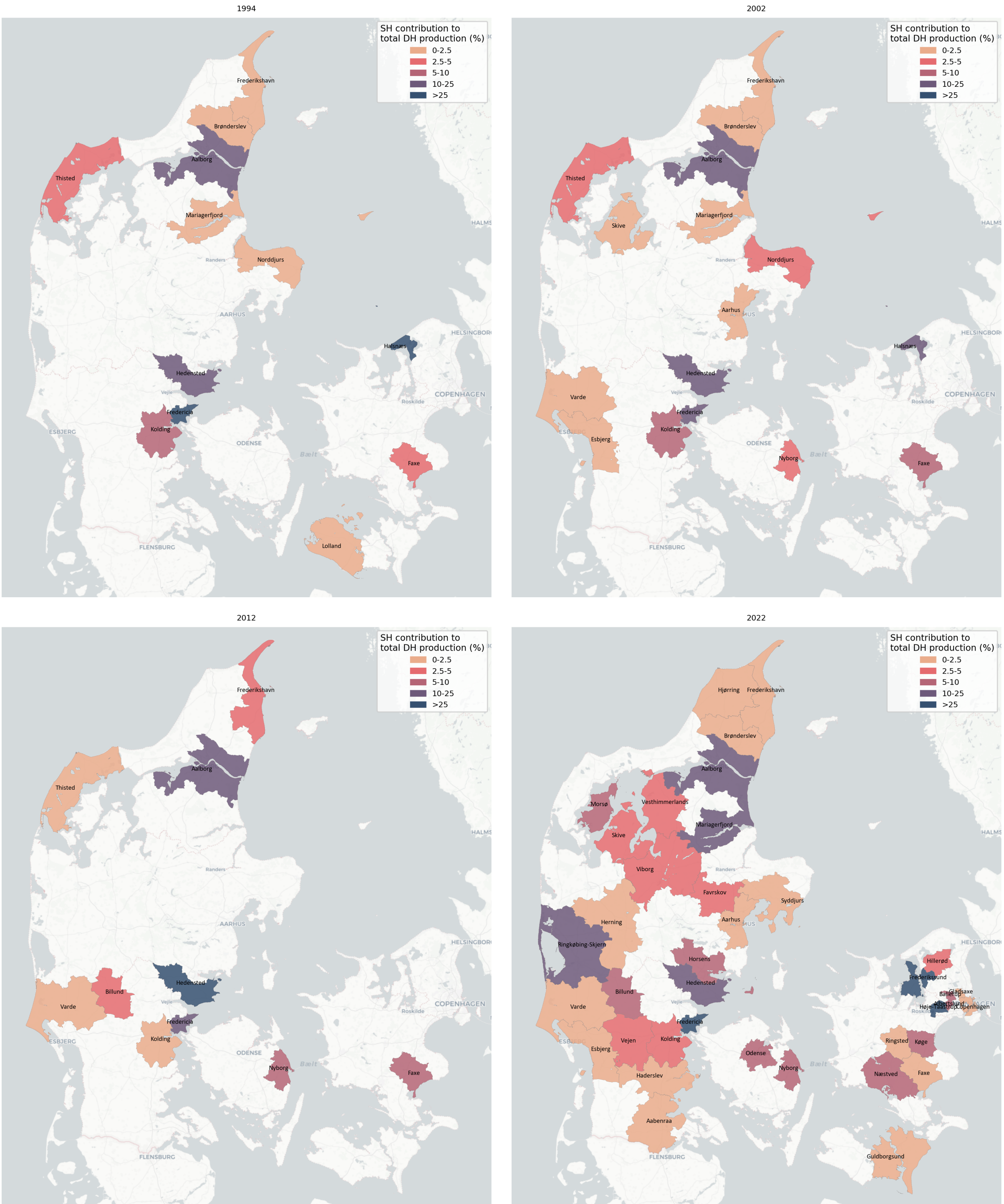

Figure 3. Proportion of the heat production in DH systems retrieved from SH in 1994, 2002, 2012 and 2022.

need to come from renewable sources. The feasibility of increasing SH integration depends on the investment costs for DH companies and the economic viability of such projects, particularly for low-temperature SH in systems that have not yet been upgraded. In addition, future use depends on industrial and commercial activity, as the relocation or closure of facilities could affect the available sources of SH.

Our results show that many municipalities not using SH in 2022 have significant untapped potential. Specific examples are the municipalities of Vejle, Middelfart, Kalundborg, Tårnby, Fredensborg and Greve, with many point sources of SH. High volumes of SH are though at modest temperature levels. These municipalities host industries such as manufacturing, food and drink processing and retail and trade, which could serve as viable sources of SH.

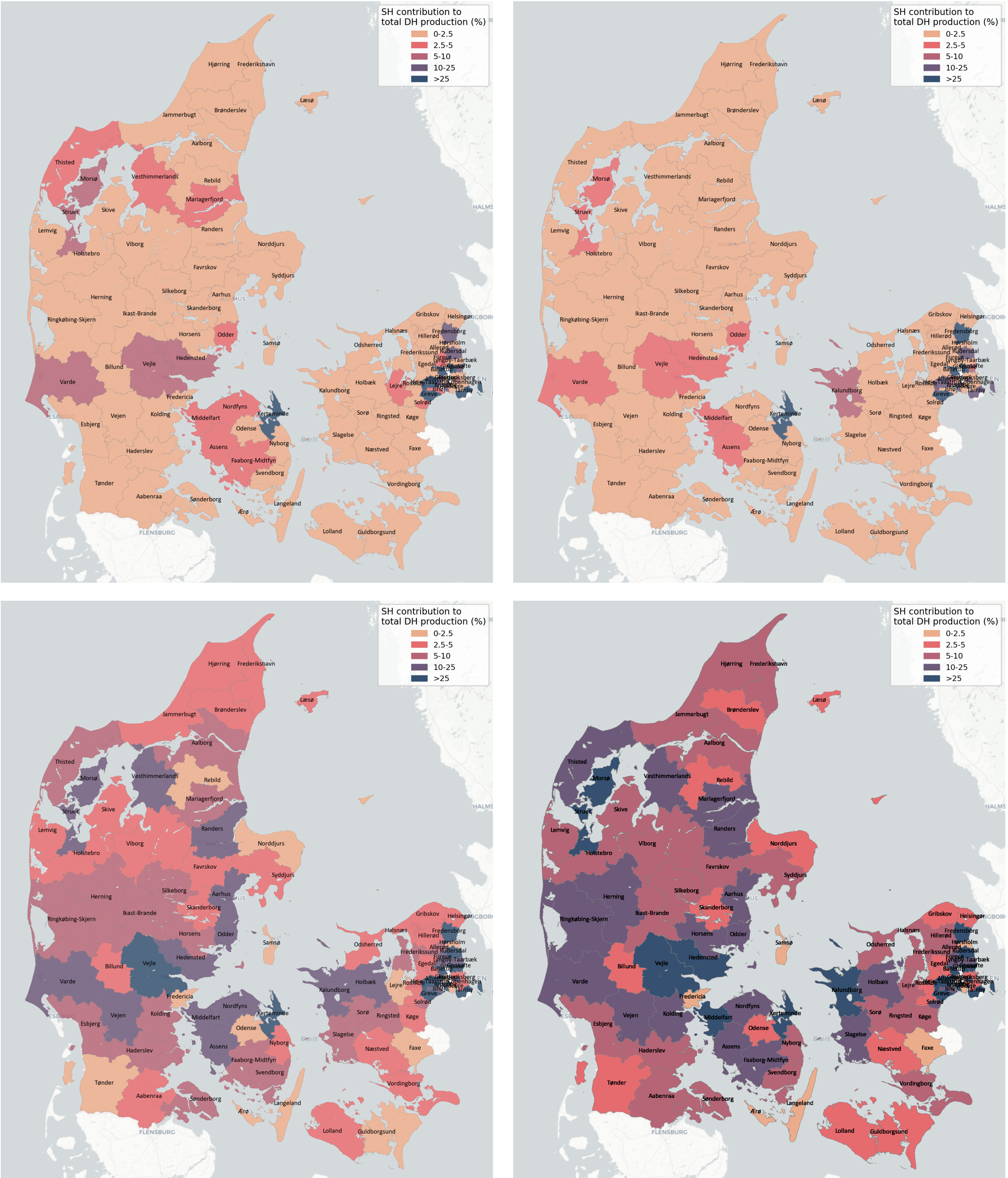

Figure 4. SH potentials in high- (top-left), medium-(top-right) and low-(bottom-left) temperatures, along with the total (bottom-right). The shares are estimated regardless the existing SH utilisation based on the 2022 DH production.

Targeted integration strategies focusing on these sectors could unlock significant contributions to DH networks.

An important consideration is that, although this analysis is carried out at the municipal level, it is the DH systems – not the municipalities themselves – that are directly connected to heat sources, and these systems are not visible at this scale. However, DH systems with high SH potential that already run across municipalities can not only meet their own heat demand, but also supply SH to neighbouring municipalities through existing DH infrastructure. The presence of well-established transmission networks facilitates this exchange, allowing a more balanced distribution of supply and demand over a larger geographical area. This inter-municipal spread of DH systems improves their overall efficiency and supports wider decarbonisation efforts by optimising the distribution of heat.

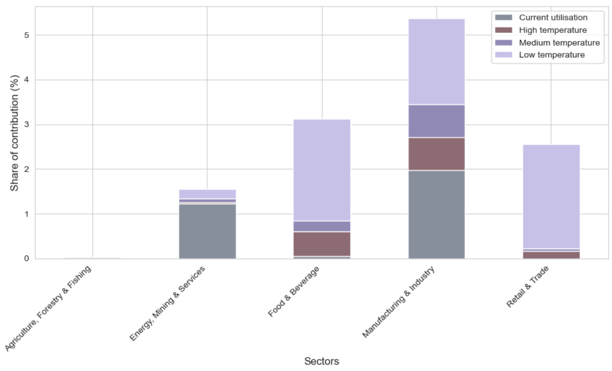

Figure 5. Share of heat production from SH recovery by sector based on DH production in 2022, regardless temperature level.

5 Conclusion

This paper presents the historical use of SH in the Danish municipalities and supports municipal and DH system planning by identifying alternative SH potentials for integration. It highlights location opportunities for future heat sources and provides a sectoral comparison based on the 2022 SH use and the potential future integration based on actual local DH production. The untapped potential is significant across the country, with high and medium temperature SH mainly located in the capital region and southern Denmark. Sectors that are not yet fully integrated, such as food and drink, retail and commerce, can contribute. However, significant potential remains constrained by low temperature and non-upgraded systems. Compared to previous studies, our analysis shows that higher potentials can be achieved.

While the methodological approach is based on basic GIS techniques, it lays the groundwork for more advanced spatial analysis in future work. The use of choropleth mapping with manual classification allows a consistent spatio-temporal comparison of SH use across municipalities. This provides a basis for further geoinformatics research, such as applying spatial clustering, change detection or trend analysis to capture temporal dynamics more accurately. Furthermore, the identification of high utilisation areas can inform future suitability mapping and cost-based assessments for the practical integration of SH into DH systems.

This research plays a critical role in local energy planning, providing insights into the optimal location of future heat suppliers, such as data centres or Power-to-X facilities. More broadly, it highlights the importance of heat recovery in DH planning for more energy-efficient systems. Future research could emphasise more on the local characteristics of the region - whether they are industrial or commercial hubs or where renewable heat sources are more limited. More localised and detailed analysis at DH system level – providing specific guidelines and strategies tailored to local conditions – would further support data-driven policy and decision making. An assessment of the cost of connection infrastructure and determining whether these connections are economically viable for the existing DH systems would also be crucial. However, careful consideration should be given to the accuracy and reliability of data sets, as uncertainties in data quality may arise. Sensitivity analysis of the temporal stability of SH sources could help to assess the risks associated with potential changes, such as the relocation or closure of industries, and their impact on long-term SH availability.

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