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Heat Roadmap Europe: Spatial assessment of district heating potential for strategic planning in Europe

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ABSTRACT

Heating is one of Europe's most energy-intensive sectors. District heating (DH) offers a key pathway to decarbonisation by integrating renewable energy (RE) and excess heat (EH) and reducing fossil fuel dependency. However, as heat demand (HD) and supply vary geographically, planning DH expansion requires understanding the spatial variability of HD, resources and cost-effectiveness of the systems. This study presents a geospatial analysis of DH potential, combining RE/EH resources and investment costs to model the distribution and economic feasibility of DH systems. Key contributions include a harmonised assessment of DH potential across European Union countries, a prioritisation framework that identifies the most cost-effective locations for DH, and an analysis of regional differences in heat market share. These insights are supported by high-resolution mapping that highlights strategic priority regions at the NUTS 2 level. The study also improves the accuracy of the Pan-European Heat Atlas, making it available as an open-access dataset and tool. The results identify regional variations in DH potential and RE/EH availability, highlighting local opportunities for efficient deployment. These findings support policymakers, regional planners and researchers in designing strategies to accelerate DH deployment toward a 55% DH market share across Europe.

Keywords

Energy planning;
Spatial modelling;
Heat atlas;
Excess heat;
GIS

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1. Introduction

Climate change action has been a major priority on the global policy agenda with the European Union (EU) taking a leading role in setting ambitious climate goals and strategies for becoming the first climate-neutral continent by 2050 [1-4]. Recently though, policy emphasis has shifted towards strengthening security and achieving sustainable prosperity for a resilient future [5]. Having achieved its goal of reducing greenhouse gas (GHG) emissions by 20% by 2020 compared to 1990 [6], the EU faces new challenges related to energy supply security [7], rising energy prices [8] and the even more challenging objective of doubling the annual GHG reduction rate to meet its 2030 environmental targets [9].

With heating and cooling accounting for 50% of final EU energy use [6], decarbonising their supply while

maintaining affordable energy prices is critical. The largest share of this energy is used for space heating and domestic hot water in residential and public buildings – approximately two-thirds – while industry consumes the remainder [10]. Among the available technological pathways, district heating (DH) is an effective means of decarbonising the heating sector, as it enables cost-effective and large-scale integration of renewable energy (RE) and excess heat (EH) sources, enhances system efficiency through sector coupling and supports flexibility in energy supply and demand management [11-14].

In 2023, DH covered 13% of the European heat market share, equivalent to a heat supply of 548.6 TWh [15,16]. The transition to RE and the penetration of EH in EU DH systems increased by 9.4% between 2022 and 2023, alongside a steady decrease in fossil fuel use [17].

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However, the DH development – including the establishment of new systems, the densification or expansion of existing ones and the changes of the fuel mix – varies widely across countries and regions. Some EU countries, such as Denmark and Finland already have high DH shares, while countries with lower shares, such as Italy and Austria, are undergoing rapid growth [17]. The development of DH systems depends on heat demand (HD) density, the available heat supply and the built infrastructure, all of which vary geographically. Technological advances in building energy efficiency measures enable lower temperature levels in DH grids, facilitating the transition from third-generation (3GDH) to fourth-generation (4GDH) systems [13] that integrate lower-temperature renewable energy sources (RES), such as geothermal energy.

Geographical and contextual conditions strongly influence though the use of such locally found resources, including industrial EH [18], data centres [19] and natural resources, such as surface water heat [20] and geothermal energy. Since HD varies with climatic and geographical conditions, and the feasibility of RES and EH utilisation depends on their proximity to DH systems, geospatial analysis is a valuable tool for identifying suitable areas for DH expansion and integration of diverse heat sources. Such analyses can inform strategic and local decisions, guide investments and support the EU's climate and energy targets.

Several projects – such as Heat Roadmap Europe [21], Hotmaps [22], ReUseHeat [23] and sEEnergies [24] – have contributed to DH planning by modelling HD and EH potentials. Scientific publications have also analysed the integration of EH in DH under different assumptions and scenarios, examining potentials and costs [21,24-31]. However, most existing studies either aggregate results at national level or rely on simplified system modelling, which limits their ability to capture spatial heterogeneity and economic feasibility at finer scales and subnational levels. To the best of our knowledge, only one previous study has provided results at regional level [32], using the EU's Nomenclature of Territorial Units for Statistics [33], a hierarchical geographical classification system that divides each EU country into three levels for statistical and analytical purposes, allowing harmonised socio-economic analyses and framed EU regional policies. Specifically, results were reported at the NUTS 3 level, which corresponds to small territorial units and is typically employed in analyses of specific diagnoses or localised outcomes [33].

However, that output remains limited in accessibility and scope regarding high-resolution modelling of technical, geographical and economic constraints, highlighting the need for an updated, spatially explicit approach capable of supporting robust DH planning across Europe. This gap restricts the ability to identify where DH deployment is most feasible at subnational scales and to quantify how regional differences in heat supply and demand conditions influence DH market shares.

1.1. Research objectives

Given this research gap and the necessity for developing realistic, region-specific DH expansion pathways in line with European decarbonisation objectives, this study presents a multistep pan-European geospatial and techno-economic assessment that identifies where DH systems are most cost-effective, evaluates their possible heat-market shares and examines how local availability of RE and EH can shape optimal DH supply mixes.. The study suggests a prioritisation system for DH expansion and assesses regional differences in heat market share aiming to achieve a 55% European DH market share in line with EU energy transition goals [17].

Key novelties and main contributions of this study include the evaluation of regional heat market shares using a cost-effective approach that accounts for investment costs, DH size and current national DH development, as well as the mapping of areas with optimal potentials for the strategic integration of RE and EH at the NUTS 2 level, corresponding to EU basic regions and providing an appropriate scale for addressing the study's analytical and policy objectives. This work contributes to the development of a pan-European heat atlas with improved accuracy, building on work performed in the sEEnergies project [24]. This heat atlas is made available as an open-access dataset and tool. Geospatial modelling is also employed to identify potential DH areas by expanding an existing DH economic assessment model [34] to estimate investment costs.

2. Material and methods

This section presents the methodological steps we followed to model the heat atlas (Section 2.1), which is a required input dataset for the DH modelling in Section 2.2. Section 2.3 briefly mentions an adjustment step to account for industrial HD, that is not included in the heat atlas model. Our methodological approach to integrating RE and EH potentials, and to assessing the DH systems

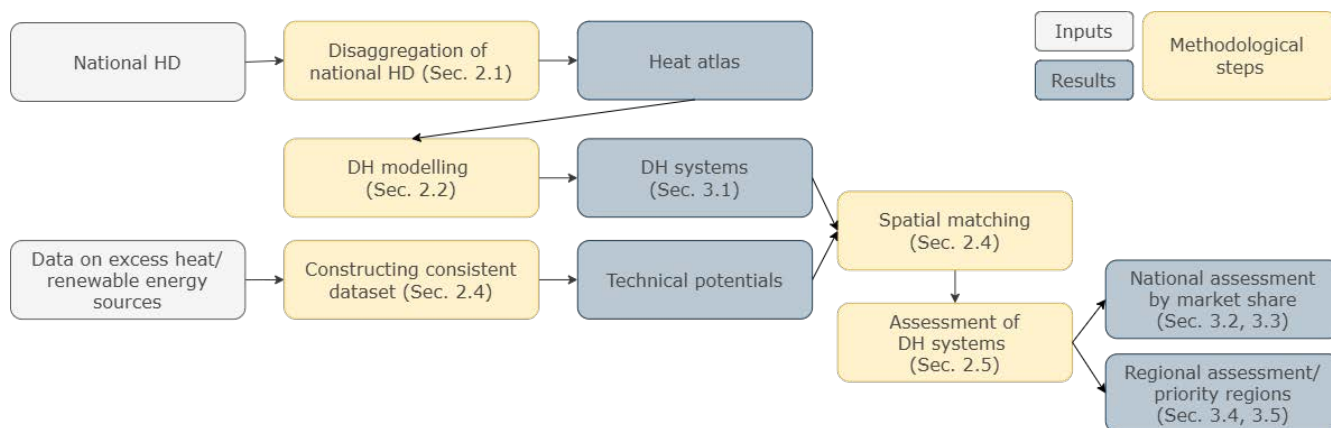


Figure 1: Schematic overview of the data, methodology and results of this study.

is presented in Sections 2.4 and 2.5 respectively. Each subsection describes the processes followed and the data used. The analysis targets the year 2050; HD data are adjusted following the approach described in sEEnergies [35], and the EH potentials are updated consistently as described in [25] or respectively in the corresponding subsections below. Figure 1 illustrates the study’s workflow, including the input data, methodological steps and produced outputs. The models are developed in Python using open-source libraries and are made available via Github.

2.1. Heat atlas

The heat mapping methodology follows a spatial disaggregation approach initially developed in the Heat Roadmap Europe project [36] and later refined in the sEEnergies project [35]. The method downscales national HD based on floor area (FA) data for residential and service sector buildings across Europe to a 1-hectare resolution. It incorporates building age classes based on the Global Human Settlement Layer [37] and further processed by the HOTMAPS project [38]. These age classes enable the assessment of energy efficiency potential by construction period. In this study, advancements over previous research include the development of an open-access model available on Github (<https://github.com/mgeorgati/heatingatlas>), the update of national HD data and a refined single-family housing FA distribution that excludes previously misclassified uninhabited areas, increasing the accuracy of the produced heat atlas. The detailed maps were used for the DH modelling described below. The demands were also aggregated to the NUTS 2 level for visualisation purposes.

2.2. DH modelling

The followed methodology is presented by Fallahnejad et al. [26]. We implemented the model retrieved from [34], that requires two input grid layers: HD and FA distribution, for which the updated heat atlas and FA density layers were used. To avoid nationwide spread of DH coverage in countries with spatially continuous HD (i.e., the Netherlands), we exclude grid cells with FA below 400 m², better reflecting realistic DH development.

The model incorporates DH pipe costs, simplified using two parameters: c1 (EUR/m) and c2 (EUR/m²), representing linear and area-dependent costs, respectively. Although actual costs vary by country and city, a uniform cost assumption is applied across all countries to ensure consistency with energy system models. The values used – 664 EUR/m for c1 and 2,610 EUR/m² for c2 – are based on updated German data from Sánchez-García et al. [39]. The uniform costs are applied to enable comparison between countries and assess where DH should be developed.

The objective of this analysis is to identify the maximum technical DH potential. Only areas clearly unsuitable for DH – due to low built-up density or remoteness – are excluded, while areas with possible future potential (e.g., due to proximity to low-cost heat sources) are retained. Potential DH areas are identified based on two criteria: (1) average distribution grid cost below a pre-defined national cost ceiling, and (2) annual HD above a set threshold. In this study, a cost ceiling of 50 EUR/MWh and a minimum annual HD of 1 GWh are applied to capture even small-scale opportunities. The model supports varying DH connection rates over time. However, to reflect the technical potential, a uniform

connection rate of 88% at the start year and 90% at the end year, consistent with mature DH countries, is assumed for all countries.

2.3. Incorporating industrial heat demands

In addition to residential and service sector HD, the model incorporates industrial HD. This is achieved by identifying industrial land use areas using the CORINE Land Cover [40] dataset and proportionally allocating national industrial HD from industryPLAN [25,41] to those overlapping with DH areas.

2.4. EH and RE potential

Several EH and RE sources can be integrated into DH systems, either directly in the case of high- and medium-temperature, or via heat pumps for low-temperature heat sources. Their integration is restricted though to spatial availability, proximity and connection distances to the DH system. To define the technical and utilisation potentials of each of the sources for the modelled DH systems, we first processed datasets for the examined sources, then performed a spatial analysis and matched the sources to the DH areas, allocating their technical potentials considering the baseload capacity of each system.

Waste-to-Energy: Although point data for existing WtE plants are available from the sEnergies project, we adopted an alternative approach that does not rely on exact plant locations. Instead, we assumed plant presence based on city size and analysed cases for cities ranging from 45,000 to 80,000 inhabitants, comparing their EH potentials to current WtE potentials. Cities with large populations ensure the economic viability of WtE plants by providing sufficient heat and electricity demand, thereby improving plant efficiency through cogeneration. The results of this sensitivity analysis identified cities with 60,000 inhabitants as the optimal size.

City sizes and boundaries were estimated using continuously inhabited grid cells from the GHS-POP layer [42]. Industrial areas from the CLC layer were overlaid on these boundaries, and a normalisation factor combining population and industrial area was applied to down-scale national WtE potentials deriving from industryPLAN, to the city level.

Industrial sources: For high-temperature industrial EH, we used the point dataset from sEnergies and aggregated the potentials of the plants within a 2 km buffer around DH areas. Updated national values from

industryPLAN were then disaggregated proportionally to the existing industrial EH capacities, assuming that large industrial sites remain in the same locations but with reduced EH potentials. EH at medium and low temperatures were also updated based on national estimates from industryPLAN. These were disaggregated based on the location of industrial areas identified in the CLC dataset, proportionally to the DH areas overlapping with these industrial zones.

Other sources: We used the point datasets provided by ReUseHeat project [43] assuming that the spatial distribution of wastewater treatment plants (WWT), metros and supermarkets may change, but their technical potentials remain unchanged in the boundaries of the estimated DH systems.

Geothermal energy: Unlike the above presented EH sources, geothermal potential cannot be derived from existing activity locations; instead, it was estimated based on the baseload HD within each DH area. The share of domestic hot water (DHW) demand from residential and service buildings was set at 20% of the HD for all EU countries, except Cyprus, Greece, Malta, and Portugal, where it was set to 25%. Baseload HD was then estimated as the sum of DH losses, DHW demand, and industrial HD, multiplied by 1.1 to account for additional load considerations [18].

Primary spatial data on areas suitable for hydrothermal and geothermal heat were obtained from the GeoDH map [44], including diverse types of basins. Due to data uncertainties and to preserve the distinction between geothermal types and temperature levels, the analysis maintained six resource categories, though results are presented as total geothermal potential.

For each DH system, technical potential was estimated by intersecting DH areas with geothermal resource layers and allocating baseload HD, assuming that suitable geothermal sources could meet the full demand. To reflect investment feasibility, only systems exceeding minimum baseload capacities of 40 MW or 70 MW were considered, as smaller systems are techno-economically not feasible. The capacity was calculated by dividing baseload HD by the number of hours in a year. The full geothermal energy potential was estimated proportionally to population and HD within areas identified as having geothermal resources.

2.5. Assessment of DH systems

After matching heat sources to modelled DH areas, we ranked them by the ratio of specific energy costs to HD

within each DH area. Unlike previous approaches, which prioritised areas with the lowest costs, often selecting small areas with low HD first, we incorporated the HD size into the ranking. This favours larger areas with high HD and relatively higher costs, reflecting a more realistic approach, as small DH systems are less cost-effective. We also ensured countries reach their current DH shares, as initial modelling left some below existing levels. The approach assumes first achieving the EU market share of 13%, then adding the ‘cheapest’ areas.

DH deployment is assessed in 5-percentage-point intervals, based on the achieved EU27-level HD shares. For each interval, HD coverage and associated grid costs are accumulated. Fixed 5% increments divide the overall EU27 target into transparent, comparable steps, allowing collective assessment and identification of countries where DH expansion is most cost-efficient at each stage. Observing how intervals fill reveals which countries should be prioritised early and which become competitive later, showing the aggregate EU trajectory and cost evolution by country.

The DH model imposes an upper cost limit of 50 EUR/MWh, preventing allocation of areas exceeding this threshold. As expansion approaches this boundary, technically suitable regions are not added, limiting the HD share at around 64% for all examined countries. Investment costs per heating unit increase sharply beyond 55%, as shown in Figure 2. Consequently, we adopt the 55% as the main analytical target for the study and identify priority regions for DH investment at the

subnational level across Europe considering the availability and size of EH and RE potentials. To this end, the modelled DH areas, along with their associated attributes (including the potential from EH and RE sources), are aggregated at the NUTS 2 level according to spatial overlap.

The NUTS 2 level offers a good balance between detailed spatial mapping and data availability, capturing regional variation, while keeping maps clear and patterns interpretable. The dataset of all modelled DH areas aggregated to NUTS 2 is available in zenodo (<https://zenodo.org/records/15363552>). We plot the results on bivariate maps using a min-max normalisation approach for costs and EH potentials. The normalised results allow regions across Europe to be identified as priorities for investment based on the size of the DH and EH and cost, assuming a holistic European prioritisation approach.

3. Results

As this paper focuses on the geospatial distribution and economic feasibility of DH systems in Europe, incorporating the potential of RE and EH, the specific results on the heat atlas and its accuracy assessment are omitted. However, the heat atlas and the associated model are available online. This section first presents the statistical results of DH modelling. It then assesses DH investment costs and EH output by EU27 market share. This leads to the regional assessment and the identification of priority regions at the NUTS 2 level.

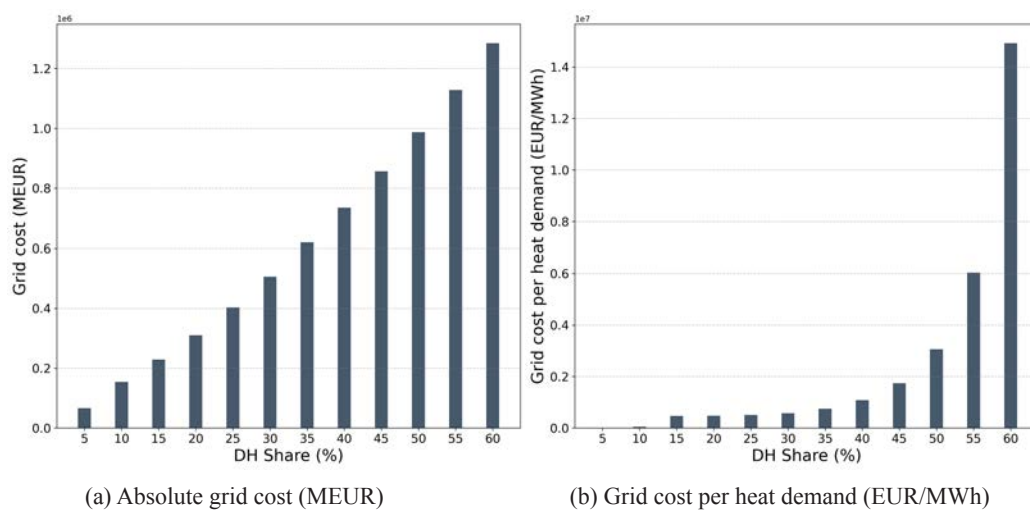


Figure 2: Incremental development of investment cost at each 5% increase in the examined EU27-wide DH market share.

3.1. Modelled DH systems

Using the DH modelling approach described in Section 2.2, a total of 47,711 areas suitable for DH development were identified across the EU27. These areas represent a combined annual potential of 1,788 TWh, corresponding to 63.7% of the EU27 HD. For comparison, the sEEnergies project identified 42,465 areas with a total potential of 1,650 TWh/a. No suitable areas were identified in Cyprus, so it has been omitted from the results presentation.

Figure 2 presents the accumulated investment costs at 5% intervals for the EU27 market share of 3GDH systems, based on the ranking method described in Section 2.5, up to 60% coverage. Absolute grid investment costs are estimated at 1.28 trillion Euros for 60% market share. While Figure 2a indicates an almost linear increase in total network expansion costs, Figure 2b – which shows the investment cost per HD – reveals that this metric more than doubles when expanding coverage from 55% to 60%. This suggests that systems added beyond the 55% threshold are smaller and less cost-efficient, resulting in a steep rise in cost per heating unit within this range.

Due to the sharp increase in marginal costs beyond 55%, it is considered more cost-efficient and realistic to adopt a target of a 55% DH market share across Europe. This threshold is therefore used for the remainder of the analysis, in which only 7,005 areas are identified as the

most suitable for DH development. These areas have a total potential of 1,543 TWh/a, corresponding to 55% of the total HD. Clearly, the selected areas represent the highest share and most dense DH of the modelled areas, with only 14% of the selected areas covering 87% of the DH demand and excluding a very large number of areas with low densities.

3.2. National-level DH assessment by market share

Table 1 summarises the national results, including the total DH potential, number of suitable areas and national shares of demand. Summary statistics are also provided for the size and capacity of modelled areas for comparability purposes. For robustness reasons, the maximum modelled DH share is also given nationally. The largest numbers of suitable areas are found in Germany, Italy, Spain and France, while the largest systems occur in the capital regions of France, Germany and Spain, and in Milan, Italy. Median DH capacities in these countries range from 71 to 101 GWh per year, whereas the smallest capacities are found in Lithuania, Estonia and Finland. It becomes evident that high national shares can be achieved, exceeding 45% in most countries, except for Romania, Portugal and Croatia, due to their more sparsely populated regions.

By levelling the results into intervals of 5%, Figure 3 illustrates the modelled national shares achievable at each stage. The figure is vertically

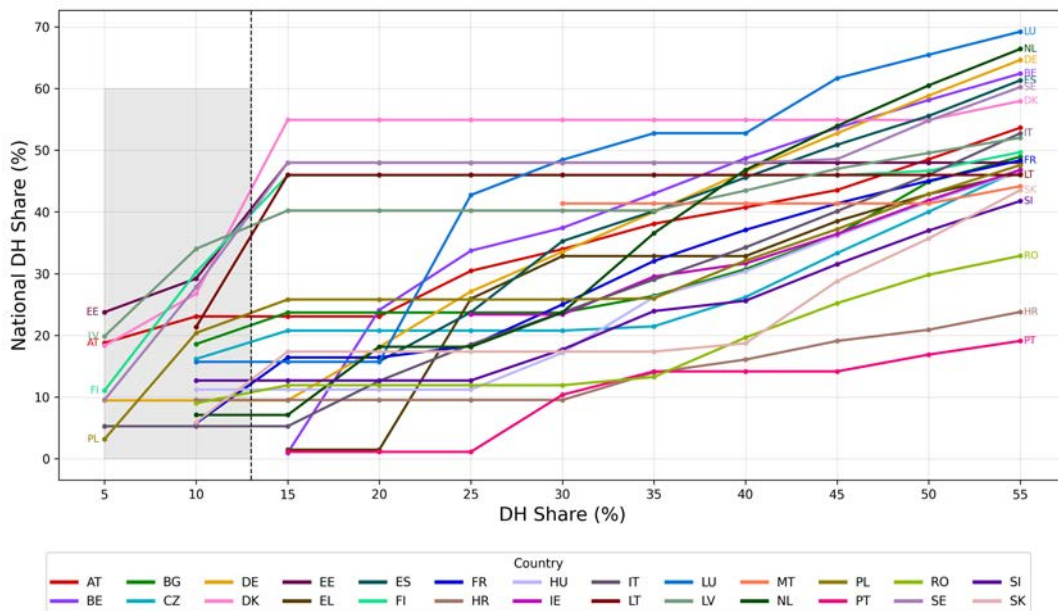


Figure 3: Incremental development of national DH levels at each 5% increase in the examined EU27-wide DH market share.

Table 1: National statistics on district heating coverage at a 55% EU27 market share.

Country	Total (GWh/a)	Max (GWh/a)	Avg.	Median (GWh/a)	Min (GWh/a)	Number of areas	National share (%)	National share (%) at 63,7% EU27 market share
AT	34,512	12,074	268	60	4	129	54	62
BE	57,863	11,518	336	80	14	172	62	70
BG	15,490	3,698	189	84	19	82	49	57
CZ	30,450	5,390	144	61	12	212	47	57
DE	442,479	24,560	236	72	7	1,873	65	75
DK	36,884	11,651	236	75	27	156	58	68
EE	6,760	3,347	73	11	2	92	48	50
EL	13,160	6,958	366	110	40	36	46	50
ES	150,429	21,010	267	71	22	564	61	70
FI	34,845	7,754	132	32	3	263	50	55
FR	201,363	44,389	365	101	7	551	48	55
HR	6,717	2,687	198	64	24	34	24	30
HU	26,345	6,339	220	81	15	120	47	56
IE	13,614	6,799	309	99	36	44	47	51
IT	187,902	18,749	159	54	3	1,181	53	66
LT	13,209	2,453	59	7	1	224	46	47
LU	6,920	2702	231	60	18	30	69	82
LV	11,466	4,377	191	44	4	60	52	57
MT	1,719	1,610	573	60	49	3	44	46
NL	78,625	13,081	308	100	28	255	66	72
PL	84,591	5,641	166	62	8	510	48	54
PT	4,071	1,974	291	112	42	14	19	25
RO	16,623	4,552	241	119	24	69	33	37
SE	47,362	7,501	247	87	3	192	60	68
SI	8,793	2,670	144	57	21	61	42	50
SK	11,445	1,556	147	82	26	78	44	52

divided, with the highlighted part showing the current national levels along the EU27 DH level based on our ranking method. This prioritises areas to reach the current national levels and the countries already having high shares follow a horizontal trend on the right side of the graph (i.e., Denmark, Finland). The slope of the lines above 13% EU27 market share indicates the pace of potential DH expansion. Luxembourg, Belgium, Austria, Germany and Spain show steady increase, starting from relatively high national levels.

In contrast, Greece and Ireland display steeper trajectories, reflecting the need for faster growth from very low current shares for EU27 to reach the first milestone of a 25% market share. Countries following a more horizontal trend in the middle part of the graph, including Romania, Croatia, Slovenia and Portugal, are expected to have later DH development. This highlights how investment priorities can be strategically aligned across countries to meet EU27 DH expansion targets.

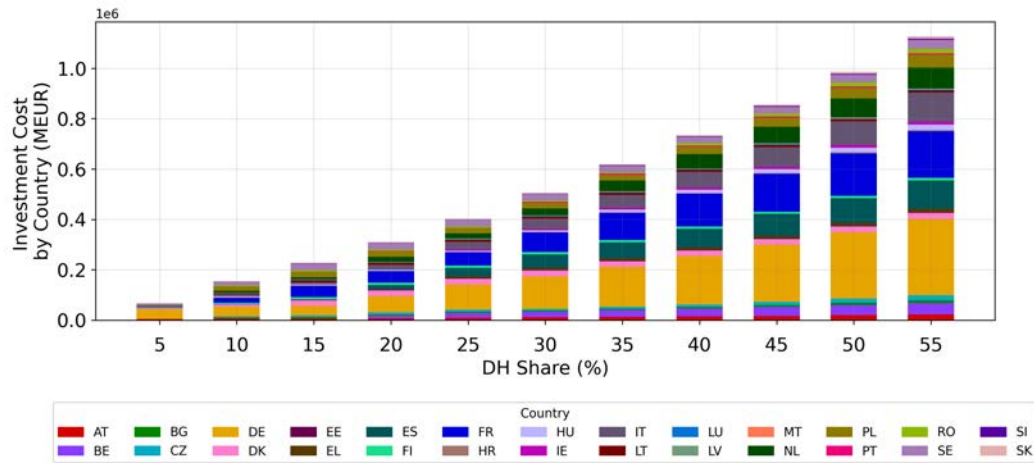


Figure 4: Incremental investment cost by country by the examined EU27 DH market share.

Figure 4 shows the accumulated grid cost by market share and by country. Germany, France, Italy, Spain and the Netherlands have the highest costs, while Estonia, Luxembourg, Latvia and Slovenia have the lowest. However, it is worth bearing in mind that these national shares and costs, and their representation up to the current DH level are not indicative of actual investments. They are the result of the modelling exercise, which are subject to the limitations of the DH model and the adopted ranking approach.

3.3. National-level EH assessment by market share

Figure 5 presents the national EH output aggregated for the three temperature levels and the geothermal

potentials. The bars indicate utilisation potentials, while the whisker lines above show the range of available potentials, even if it is not in proximity to DH areas. DH demand is also displayed for comparison. Overall, utilisation potentials can cover a substantial share of DH demand in most countries, despite geographic constraints and the baseload capacity limits.

The gap between utilisation and full potentials varies considerably among countries, reflecting the influence of the geographical distribution of HD and sources, as well as their spatial proximity. In the Netherlands, Denmark and Austria, most of the identified sources can be effectively utilised within the modelled DH areas, potentially due to the proximity of EH resources to

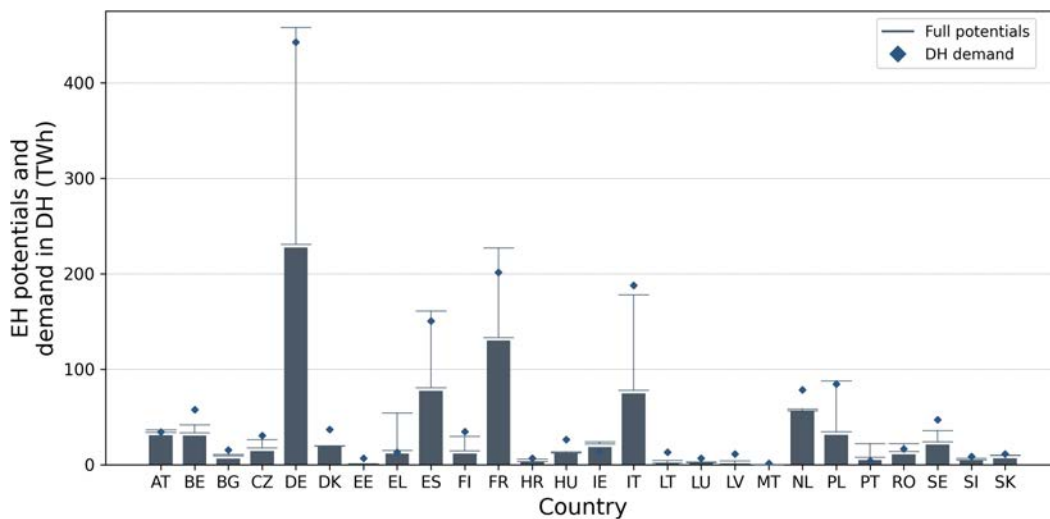


Figure 5: Aggregated potentials of RE and EH in DH areas for 55% EU27 market share.

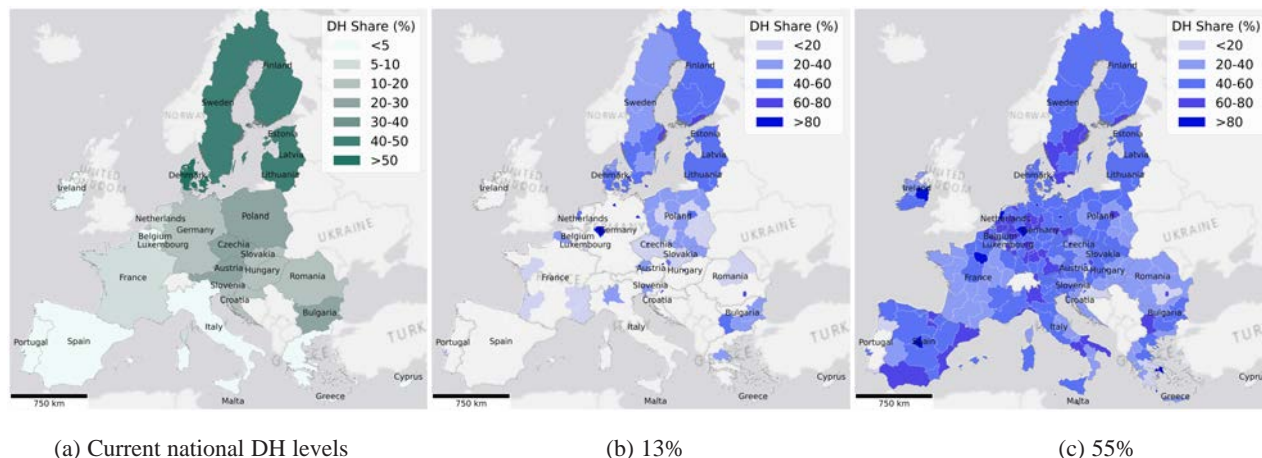


Figure 6: Spatial distribution of DH levels. The percentages indicate the DH level mapped against the aggregated to the NUTS 2 regions HD from the heat atlas.

expanded urban centres. In contrast, utilisation potentials in Spain, Italy, Germany and France are markedly lower than their respective technical potentials, particularly regarding the utilisation of geothermal energy and EH. This leads to the conclusion that even though these countries have resources that could cover a large share of their DH requirements, the resources cannot be directly connected to DH areas.

3.4. Regional DH and EH assessment

National-level DH data are limited but estimates from Mathiesen et al. [15] provide an overview (Figure 6a). City-level information on DH coverage is even scarcer. Both HD and DH infrastructure are spatially discontinuous, varying sharply in density and intensity. EH availability is likewise highly heterogeneous, shaped by geography and the location of heat-producing activities (e.g., WWT plants, supermarkets) as well as natural resources (e.g., solar exposure, rivers, lakes, geothermal). This strong spatial variability underscores the need for regional-scale assessments that capture local potentials and enable robust evaluations of cost-effectiveness.

Based on the DH modelling and the adopted ranking methodology, the maps in Figure 6 show the spatial distribution and level of DH at the NUTS 2 level in Europe. At the ‘current’ level of 13% DH (Fig. 6b), all NUTS 2 regions of countries around the Baltic Sea (excluding Germany) have a significant proportion of their HD covered by DH – typically around or above 40% – thereby meeting a substantial proportion of the national demand. The Czech Republic, Slovenia, Slovakia and Bulgaria

also have spatial coverage across most of their regions, albeit on a smaller scale. In Western Europe, more island-like areas are identified, such as in the periphery of France, metropolitan regions of Germany and the Low Countries. Referring to the target of 55% in Figure 6c, there are varying levels of DH coverage across European regions, with dark purple/blue shades indicating a potential coverage of over 60% of a region’s demands. Specifically, spatial and capacity-based intensification of DH development is evident in the Low Countries, Germany and Spain, and to a lesser extent in Italy and France.

It should be noted that the map of the ‘current’ distribution does not reflect the actual spatial extent of existing DH systems, but rather an assumed distribution derived from our ranking approach. Several regions with established DH networks – such as the Paris metropolitan area in France or Munich in Germany – are absent because they did not meet the cost- and size-based prioritisation criteria applied at the national level.

Examining the EH potentials by heat source, Figures 7 and 8 show the size of utilisable EH and geothermal energy as a percentage of the HD in the modelled DH at NUTS 2 regions. Figure 7 maps the EH potential at the three different temperature levels. High-temperature potential is identified in several regions of Romania, Greece and northern Spain. Large medium-temperature source potentials are identified across Europe, primarily in Ireland, Romania, Greece and Spain. Lower shares are found in most regions from low-temperature sources, however requiring the use of heat pumps to increase the temperature to levels suitable for 3GDH.

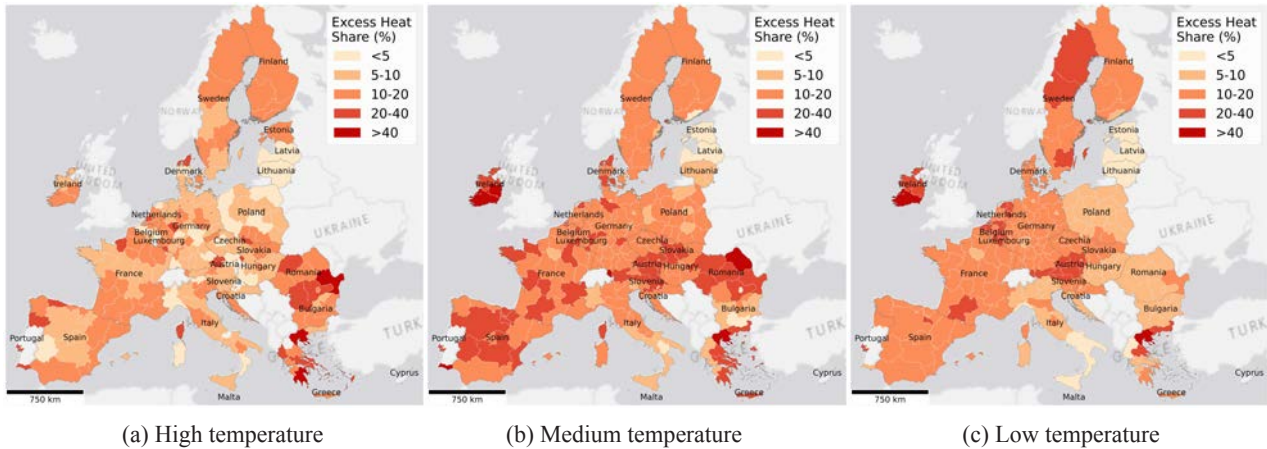


Figure 7: Potentials of EH from the explored sources per DH demand by temperature level at 55% EU27 market share.

Figure 8 shows geothermal utilisation potential under two assumptions: first, implementation in areas with minimum capacity of 70 MW (Fig. 8a) and second, in areas with at least 40 MW (Fig. 8b). This assumption is crucial because geothermal investment costs in DH systems are high and generally uneconomical for small networks. The importance of detailed, high-resolution spatial analysis becomes clear, as geothermal potential is unevenly distributed and serves areas with different DH capacities. Central European countries benefit most, with large potential in France, Germany, Italy and Ireland, followed by Poland, eastern and southern Spain, and Austria.

3.5. Identification of priority areas at NUTS 2 level

The maps of Section 3.4 allow the identification of regions that could benefit from EH within their networks. However, several of the above discussed regions in Southern Europe are characterised by low HD compared to regions of Northern Europe. Therefore, while this visualisation approach highlights local opportunities, it is not suitable for drawing conclusions about investments at a pan-European level.

For this purpose, we further present the data after normalisation on the bivariate maps of Figure 9. In this case, DH availability, EH potentials and investment

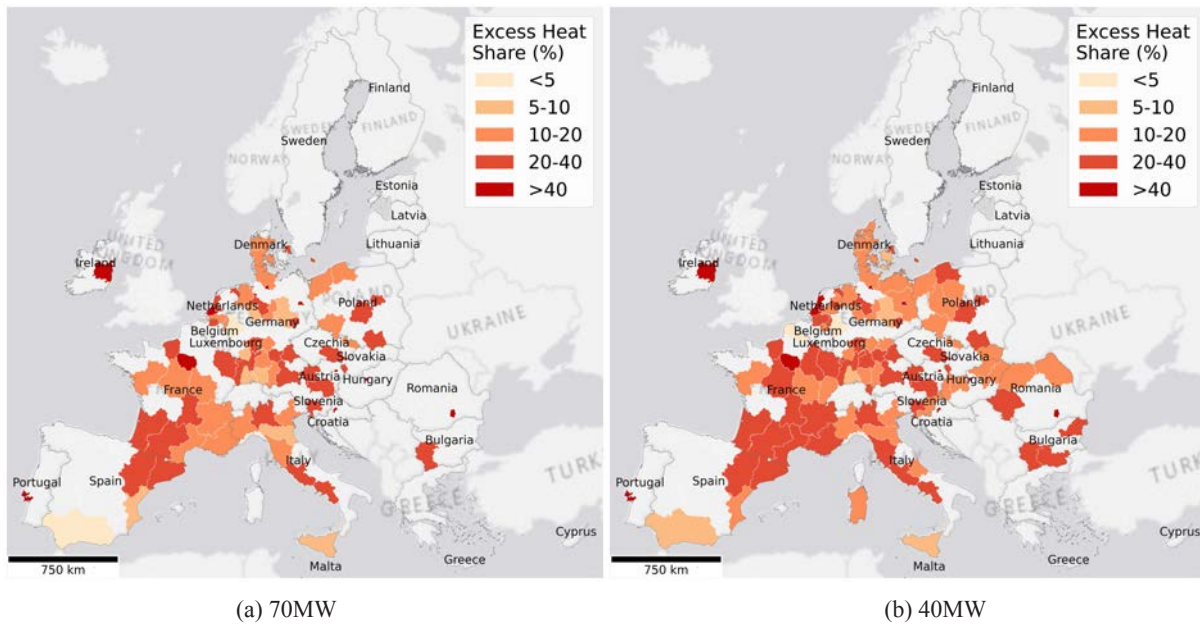


Figure 8: Utilisation potential of geothermal energy at 55% EU27 market share under two capacity thresholds: areas with a minimum base-load demand per DH area of 70 MW (left) and 40 MW (right).

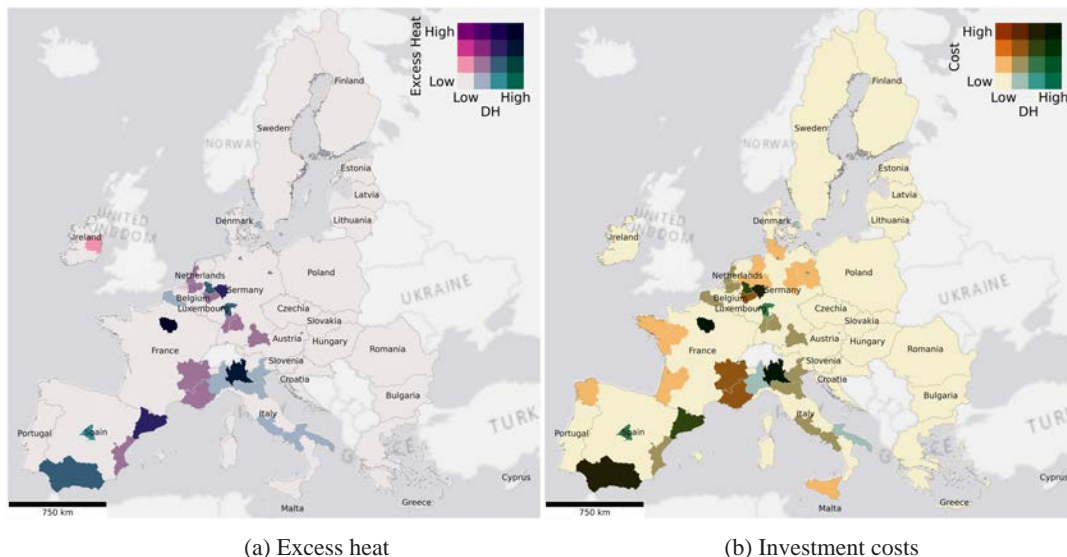


Figure 9: Regional comparison through bivariate mapping. The maps show the normalised values of EH (left) and investment costs (right) in relation to DH potential at a 55% EU27 market share. Each attribute is divided into 0.25 intervals, with 0 representing the lowest value in Europe and 1 representing the highest.

costs are shown as normalised values across all NUTS 2 regions in Europe, where 0 (Low) represents the lowest value observed in Europe and 1 (High) the highest.

Specifically, in each map the shading combines these two attributes; DH in green on the horizontal and EH and investment costs in purple and orange on the vertical axis of the respective maps. Darker colours indicate regions where both DH demand and EH or costs are relatively high compared to the European range, such as in Northern Italy and Germany. Lighter colours show regions with lower proportions of either or both attributes, as in the case of Greece where both DH and EH and costs are low relatively to other NUTS 2 regions in Europe (light shades of pink and yellow respectively). Such an approach provides a pan-European comparative perspective at the NUTS 2 level and supports regional prioritisation of investments and planning efforts.

Areas with high DH and EH potential or investment costs are highlighted in darker colours on both maps. These include Lombardy (Italy), Île-de-France (France), Arnsberg (Germany) and Catalonia (Spain). Interestingly, the mapping reveals that Eastern and Midland Ireland, ranked in the second EH scale row (0.25 - 0.5), offer good EH potential and are cheaper than regions indicated in light orange in Figure 9b, making them a more cost-efficient choice. Similarly, northern Italian regions with comparable EH potential, indicated in light blue in Figure 9a, show that Piedmont (west of Lombard) has

lower costs than Emilia-Romagna and Veneto to the east. Several western Germany regions stand out, with Darmstadt and Dusseldorf showing high DH potential and low costs, but low EH potential.

4. Discussion

This study applies a multistep geospatial analysis to assess the distribution and economic feasibility of DH systems in Europe, incorporating the availability and capacity of RES and EH. The study contributes to the existing body of literature by evaluating the regional heat market shares using a cost-effective approach that accounts for investment costs, DH size and current national DH development. We discuss the results under the scope of the three main methodological approaches applied, along with their associated limitations.

DH modelling and assessment

The present study initiates building upon existing modelling approaches on the development of an updated and improved Pan-European heat atlas and DH assessment. We suggest a prioritisation framework analysing DH market shares in percentage intervals, enabling phased deployment targets and intermediate milestones. In this way, the national targets required to achieve a common European goal through incremental steps are presented alongside the associated national investment requirements.

Despite the model's exceptional performance in capturing areas with high heat densities, we recognise its limitations, particularly regarding cost parameters, as inflation is not considered. The model caps supply costs at 50 EUR/MWh, with an annual HD threshold of 1GWh. This limits expansion beyond this threshold and reduces the accuracy of cost estimates above 65% HD share. Compared to the study by Ref. [26], which used similar ceiling thresholds of 30–42 EUR/MWh depending on the country, and 5 GWh/year, achieving a maximum HD coverage of 35% in the EU27, this study ensures smaller, yet still meaningful, areas are captured, while maintaining a realistic cost ceiling and maximising DH potential coverage. The maximum potential varies by country and may restrict the interpretation of percentage intervals. Although actual costs differ significantly between countries and between urban and rural regions within countries, uniform parameters allow comparison and identification of where DH should be developed. These differences are also affected by experience with DH and labour costs. The model recognises areas that are unsuitable for DH due to remoteness or low building density. However, on certain occasions, it has produced large, almost nationwide systems because of the spatially continuous HD. This has required manual adjustments to the heat atlas input. The next steps should include modelling adjustments to differentiate the costs and heat losses between 3GDH and 4GDH, by incorporating realistic and technologically advanced future scenarios.

Although the 55% DH share threshold allows for a consistent pan-European assessment, it introduces a selection effect by excluding areas with higher costs and lower heat densities. This affects the prioritization of regions and countries that are less favorable for DH deployment. To assess the robustness of the results with respect to this threshold, the size and spatial distribution of the excluded DH areas is assessed based on Table 1. On average, 12% of the nationally modelled DH HD is excluded due to the threshold. However, this effect varies across countries. Croatia, Italy and Portugal are the most sensitive, with 19–24% of modelled DH HD excluded. Lithuania, Malta and Estonia are minimally affected, with less than 5% excluded. While the overall pan-European findings are robust, these results indicate that the choice of threshold has a more pronounced impact in countries with lower heat densities and higher system costs with national-level implications.

EH modelling

The EH analysis combines several heat-source datasets and, where necessary, adjusts or develops new datasets following top-down and bottom-up approaches. Spatial relationships between EH sources and DH areas are explicitly considered, as connection distance directly affects cost and efficiency.

Reported EH potentials vary widely in the literature [27]. For validation, we selectively compare our results with previous studies by category. Future industrial activity is assumed to be dynamic: some fossil-fuel-based industries may electrify or close, reducing heat output. However, industrial facilities remain spatially constrained to designated industrial zones, which guides their disaggregation to local areas. Manz et al. [45] estimate 59 TWh/a of industrial EH suitable for DH in the EU27, compared to 52.5 TWh/a in our study. Bühler et al. [46] find industrial EH could supply 5% of Danish DH demand; we estimate 7.4%. WtE potentials are derived from future assumptions linked to city size. Unlike Persson et al. [32], who identified WtE facilities via a bottom-up analysis in 16 countries, we estimate potentials across all EU27 and generally obtain higher values.

Geothermal potential is assessed at DH level based on spatial overlap and baseload capacity. Our estimates align closely with Manz et al. [27] for Germany (61 TWh vs. 60 TWh) and Spain (11.63 TWh vs. 11.69 TWh) but differ substantially for Poland (9 TWh vs. 24 TWh). These differences likely reflect our capacity restrictions, which exclude small DH areas. Importantly, geothermal integration is limited by high investment costs and is rarely viable for small networks. It is important to highlight here that the geothermal energy is calculated upon the annual baseload heat demand of the nearby DH area and that full-load hours are not modelled, since the hourly temporal resolution is outside of the scope of this study.

Although we consider a broad range of high- to low-temperature sources, installing heat pumps for medium- and low-temperature EH involves additional costs that lie beyond the scope of this geospatial analysis. Our study therefore focuses on heat sources consistently examined in prior research, updating capacities where possible. Nonetheless, several additional sources – such as biomass, rivers, solar thermal, and data centres – could further enhance DH integration of RE/EH. Specifically, solar thermal, which is primarily restricted by land availability given the sufficient levels of solar

radiation across the EU, has the capacity to provide low-cost renewable heat during periods of high solar availability, particularly when combined with seasonal thermal storage. Its capacity to function effectively at low temperatures makes it ideal in the transition to 4GDH systems. Biomass heating networks exhibiting enhanced efficiencies have the potential to make a substantial contribution to climate change mitigation and emissions control, thereby enabling a more flexible operational framework. However, given the constraints surrounding the utilisation of sustainable biomass and the competing demands from diverse sectors, its implementation in DH systems would result in a comparatively modest contribution to the energy mix. Future work should incorporate these sources and advance their spatial representation to improve estimates of RE/EH potential.

Assessment at regional level

HD and DH infrastructure vary in density and are shaped by geography. This spatial heterogeneity underscores the need for regional-scale assessments that capture local potentials and enable robust evaluations of cost-effectiveness. Building on this perspective, we summarise regional RE/EH potentials at the target stage, revealing substantial sub-national disparities in DH potential and resource availability. Our visualisations highlight local opportunities for DH expansion and support planning in relation to RES or otherwise wasted heat sources. Unlike most previous studies limited to national analyses [47,48], this work quantifies and maps multiple EH sources at NUTS 2 level and makes the dataset openly available.

To optimise interpretation and enable regional prioritisation, results are normalised to highlight areas with the highest DH and EH potentials relative to costs. Unsurprisingly, major urban centres emerge as priority zones, reflecting both the benefits of DH intensification in dense areas and operational advantages of nearby RE/EH resources.

Current DH levels and costs are based on a ranking approach and do not represent actual system locations or sizes. Aggregating results at NUTS2 offers clear advantages: outputs remain visually interpretable, patterns are distinguished without fragmentation, and consistency with socioeconomic datasets facilitates cross-country comparisons. However, DH operators do not follow administrative boundaries, and some modelled areas span multiple regions. While this ensures comparability,

higher spatial detail would better support local planning – identifying industrial clusters with high EH potential, locating geothermal sites, or assessing proximity of WtE facilities. Such granularity would enable more accurate investment decisions. Finally, aggregation introduces potential biases through zoning and scaling, as known modifiable areal unit problem [49]. As most data values are concentrated at the lower end of the scale, the classification method groups them into similar classes, making small differences difficult to distinguish.

5. Conclusion

This study applies a multistep geospatial analysis to assess the spatial distribution and economic feasibility of DH systems in Europe, considering the proximity and capacity of RE/EH sources to the DH areas. It contributes to the literature by estimating regional heat market shares through a cost-based approach that accounts for investment costs, DH size, and current national DH development. These findings offer a transparent basis for regional energy planning, support prioritisation of DH expansion in line with EU decarbonisation targets and enable policymakers to design targeted incentives and infrastructure strategies that accelerate RE/EH integration.

Methodologically, the study advances geospatial energy modelling by assessing DH potential across all EU27 countries, integrating EH and investment costs with mapping and visual interpretation at NUTS 2 level. It improves the Pan-European Heat Atlas, now available as an open-access dataset and tool. For the academic audience, this work introduces a scalable, reproducible framework for regional heat planning that bridges technical, economic, and spatial dimensions, adaptable for comparative studies, scenario analysis, and integration with broader energy system models.

Unlike individual heating solutions, grid-based systems such as DH leverage shared infrastructure, improving equitable access to affordable, reliable, and clean energy—particularly where RE/EH sources are available. DH development should capitalise on local opportunities while aligning with sector integration, for which geographic tools like ours are essential. High-resolution spatial outputs support modelling at local, regional, national, and pan-European levels, enabling robust scenario development, comparison of transition pathways, and resilience assessments within energy system modelling.

Ultimately, this study underscores the critical role of geography in shaping future energy systems. Variations in HD driven by density, climate, demographics, and urbanisation, combined with the spatial distribution of heat sources, are fundamental for planning sustainable infrastructure. Future systems will increasingly involve large-scale heat producers such as data centres and Power-to-X facilities, requiring integration into planning frameworks. Moving toward higher-resolution modelling beyond NUTS 2 will enable site-specific strategies, including identification of industrial clusters, optimal placement of WtE facilities, and targeted geothermal deployment. Geospatial intelligence is thus essential for achieving cost-effective, resilient, and decarbonised heat supply systems across Europe.

5.1 Limitations and future research directions

This study is subject to several structural limitations relating to modelling, cost and technological assumptions. The DH model relies on harmonised cost parameters and simplified economic inputs to enhance comparability at the EU level. However, it does not capture variations in investment (i.e., due to ground conditions or existing infrastructure), local market conditions or financing structures at country, region or city level, that could significantly vary across Europe and in each country. Consequently, the results should be interpreted as indicative of structural potential rather than investment projections. Additionally, a sensitivity analysis of the results with respect to the parameters of the DH model — including, but not limited to, the cost ceiling and the annual HD threshold — would improve the quality of the results. Future research is encouraged to quantify the impact of these parameters more systematically.

The analysis is limited to 3GDH systems and alternative supply options, such as solar thermal or biomass, are not explored. These technologies can play a complementary role in future DH systems, particularly in regions with abundant solar resources or well-established biomass supply chains. Their inclusion in future studies may yield advanced diversification pathways and local decarbonisation strategies. Future research should integrate spatially differentiated techno-economic data, expand the portfolio of heat supply technologies and assess the implications of 4GDH systems within a consistent modelling framework for realistic and technologically advanced future scenarios.

Another limitation is the temporal resolution. While the analysis is based on annual energy balances within a GIS-based framework, which is suitable for strategic spatial planning, it does not capture intra-annual dynamics, peak-load interactions or operational flexibility. Coupling DH systems with thermal energy storage technologies is not modelled, since their performance and economic value require an hourly resolution, similarly to the full-load hours for the calculation of geothermal capacity. Supporting information can be retrieved in [25], which examines the integration of thermal storages. However, it is recognised that modelling with a higher temporal resolution directly within the local assessment is crucial for a comprehensive evaluation of system flexibility, sector coupling and storage integration.

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