Heat Roadmap Europe

Heat distribution costs

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Heat Roadmap Europe: Heat distribution costs

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ABSTRACT

This analysis elaborates further the concept of physical and economic suitability for district heating in EU28 by an aggregation regarding key dimensions such as land areas, populations, heat demands, and investment volumes. This aggregation is based on a resolution on hectare level by slicing the total land area into 437 million pieces. Results show that heat demands in buildings are present in 9% of the land area. Because of high concentrations in towns and cities, 78% of the total heat demand in buildings originate from dense urban areas that constitute 1.4% of the total land area and 70% of the population. Due to these high heat densities above 50 MJ/m^2 per year, the paper evaluates a setting where district heating is individually expanded in each member state for reaching a common 50% heat market proportion in EU28 at lowest cost. At this saturation rate, the aggregated EU28 district heat deliveries would increase to 5.4 EJ/a at current heat demands and represents an expansion investment volume, starting from current level of 1.3 EJ, of approximately 270 billion euro for heat distribution pipes. Given the current high heat densities in European urban areas, this study principally confirms earlier expectations by quantitative estimations.

1. Introduction

In the pursuit of improved energy efficiency and reduced primary energy demands in the European Union (EU28), one key area of increasing interest in recent years is the heat market for residential and service sector buildings. This heat market, which in 2015 consisted of 10.8 EJ of heat provided for space heating and domestic hot water preparation, has traditionally been dominated by fossil fuels such as natural gas, oil, and coal. It represents a segment of the European energy system where significant progress towards energy demand and emission reduction targets may realistically be reached, given that appropriate measures are implemented. From a European policy perspective, this interest has resulted inter alia in a series of recent communications and legislative acts in the promotion of e.g. energy efficiency standards for buildings [1,2], energy system synergies [3–6], as well as dedicated strategies for the heating and cooling market [7–9].

The objective of this study is to assess and evaluate the suitability for district heating in the EU28 heat market for residential and service sector buildings. This is motivated by the fact that district heating, a heat supply technology that by its fundamental idea incorporates energy efficiency and resource synergy principles [10,11], on average has remained a marginal occurrence in the EU28 (~12% residential and service sector heat market share in 2015 [12]). Given that district heating occupies residential and service sector heat market shares in the order of 40%–60% at its highest deployment levels among contemporary member states [12,13], it is relevant to investigate the conditions for a further expansion of this heat supply technology also in a general European context. By increased deployment levels of district heating, the European community could expect to benefit from reduced primary energy demands, reduced dependency on energy imports, increased security of supply, as well as lowered greenhouse gas emissions from activities and processes for the provision of heat to residential and service sector buildings.

Several possible dimensions may be used to distinguish suitability for district heating. In this work, two such dimensions are elaborated in the main. First, physical suitability is expressed here by use of the quanta heat density, i.e. the aggregated sum of building heat demands in a given land area, which in turn is established on the basis of two underlying concepts; population density and heat demand. Secondly, economic suitability is

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expressed here by use of the distribution capital cost for network heat distribution, i.e. the annuitized network investment cost by unit of delivered heat. In addition, two circumstantial dimensions which may influence the suitability for district heating on member state heat markets, i.e. current deployment levels and lowered future heat demands, are part of the study analysis and discussion, respectively. Other possible dimensions, however, such as for example national heat market compositions, investment strategies of utilities, cultural preferences etc., are excluded here as they lie beyond the study scope.

The present paper may be regarded as an elaborated second part and a continuation of the work presented in Ref. [14], which laid the foundation for an analytical approach whereby to assess the feasibility of district heat distribution by the introduction of a distribution capital cost model. If the primary contribution of this original work consisted in the theoretical reformulation of linear heat density, applied there to a limited selection of 1703 heterogeneously shaped city districts in 83 Northwestern European cities, the value added here consists in its uniform application on a homogenous hectare grid representation of the entire building heat market in EU28. Hereby, the significant progression in this paper does not relate essentially to a further development of the applied method, but instead to a vast increase in studied objects made feasible by the development of a comprehensive assembly of Geographical Information System (GIS) datasets for the EU28 residential and service sector heat market. The novelty of this work is thus the considerable extension of scope and level of detail in terms of the targeted and analysed land areas themselves, since EU28 has a total land area of 437 million hectares. Moreover, the analyses in this paper have been updated by using data parameters representing reference year 2015 conditions.

In the introductory section of [14], it is stated that “the main additional cost for a district heating system compared to a local heat generation alternative is the unavoidable cost of heat distribution”. This implies that, to be competitive on a heat market, the customer cost of district heat must be lower than the cost of the local heat generation alternative. However, the proportion of the heat distribution cost in the total cost for district heat is under direct influence of the heat density of the supplied land area. This situation is illustrated in Fig. 1 with a principal example where the local heat generation cost is 20 euro/GJ and the district heat price should be 18 euro/GJ in order to stay competitive. The addition of the heat distribution cost for district heat is however counteracted by a considerably lower primary energy cost (heat generation cost) compared to the local heat generation case, primarily because of economy-of-scope (access to recycled heat), but also some influence from economy-of-scale (large volumes).

At dense and very dense conditions, the heat distribution cost constitutes lower proportions of the total cost, since short distribution pipes can be used per unit of heat delivered. This enables higher abilities to pay for recycled excess heat from industrial and commercial activities. On the other hand, at moderate and sparse densities, the heat distribution cost component becomes a more considerable proportion of the total cost, since longer pipes are required. At very sparse densities, the heat distribution cost becomes higher than the competitive district heat price, giving no space at all for the primary energy and heat recycling costs. At extremely low heat densities, consequently, district heating is principally not competitive.

In a long-term perspective, as heat densities are expected to decrease, the heat distribution cost will in general constitute a relatively higher proportion of the total cost. In this situation, local availability of low-cost heat sources should have a decisive influence on the future feasibility and competitiveness of district heating. Hence, high distribution costs reduce the possibility for remuneration of recycled heat.

If, then, it would be possible (*i*) to superimpose a square grid structure upon the entirety of the EU28 land area, and (*ii*) to determine each cells’ residential and service sector building heat density (physical suitability), a foundation by which to uniformly assess specific investment costs for district heating (economic suitability) would have been found. If so possible, two main modes of representation of these metrics would then be available, one being their actual spatial distributions (raster map layers), the other

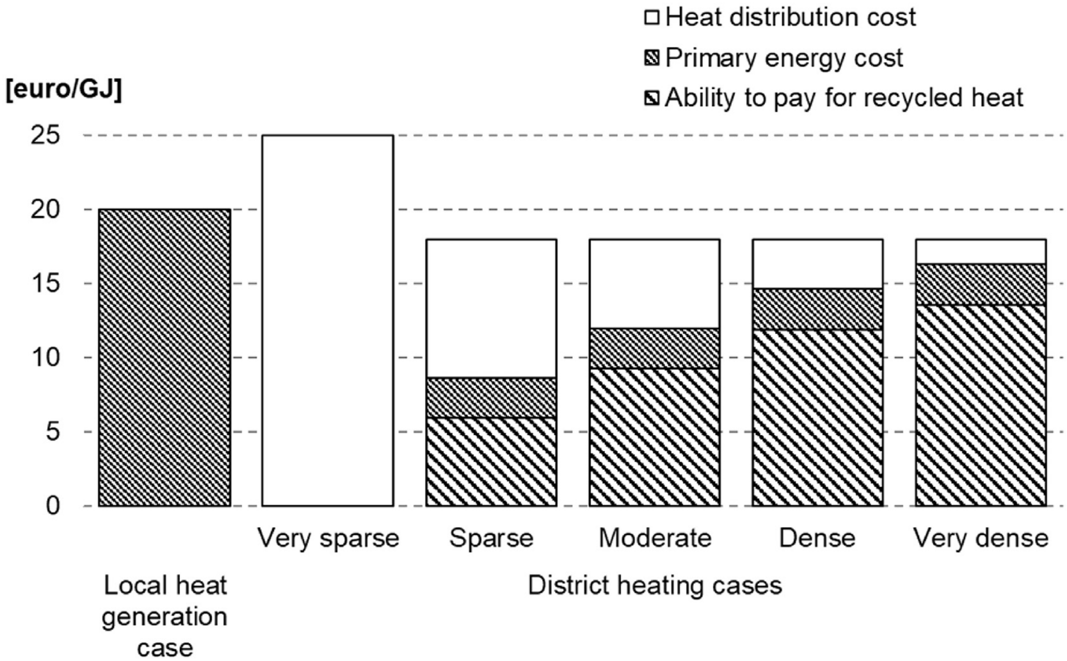

Fig. 1. Example with cost structure comparison between one local heat generation case and five district heating cases with respect to heat distribution costs, primary energy costs (heat generation), and the abilities to pay for recycled heat (excess heat recovery). The five district heating cases consider different concentrations of the heat demands.

being their various aggregates on local, regional, and national levels (summary graphs and tables). In all its brevity, this proposition is in fact the central idea of this whole work.

From these considerations, the aim of this study is to answer the following four research questions concerning the residential and service sector areas within the EU28 member states:

- What is the physical suitability for district heating with respect to heat densities?
- What is the economic suitability for district heating with respect to heat distribution costs?
- How do current deployment levels of district heating relate to economically suitable levels?
- What is the simple aggregated answer to why district heating can be viable concerning physical suitability?

Our ability to provide answers to these questions should be understood as a result of several years of dedicated and consistent cooperation between the authors in the continued development of approaches and perspectives ever since the distribution capital cost model was first conceived. The Heat Roadmap Europe concept, i.e. combining highly resolved temporal energy system modelling with highly resolved spatial energy mapping [15,16], had, already when it was first conceived in 2011, the outputs from the first distribution capital cost model publication as one of its fundamental pillars. After two general European pre-studies, the first in 2012 [17], the second in 2013 [18], the concept was further developed and applied explicitly to five EU28 member states in the Stratego project (2014–2016 [19,20]), where after the Heat Roadmap Europe project began within the Horizon 2020 research program [21].

In terms of mapping the spatial distribution of building heat demands, a common denominator through this sequence of projects, the development of tenable approaches whereby to descend from the coarser square kilometre grid resolution level to hectares (100 m × 100 m) has been a key priority. The important rationale for this ambition is the fact that suitable conditions for district heating, which very well may be found also in smaller settlements and city district areas, may not properly be represented at the square kilometre level. The main advantage of using a uniform square grid representation instead of an adaptive grid approach (e.g. quadtree), is further that computations for overlapping cells, involving wide intervals of discrete number values from several different layers, may be performed in a consistent and easily comparable way. To our current knowledge, such highly resolved assessments of the economic suitability for district heating has never previously been published for the complete EU28 residential and service sector.

The paper is structured with a materials and methods section (Section 2), which positions the current work in the contemporary tradition of remote sensing and describes, separately for the two suitability metrics, the general approaches and theoretical concepts used to arrive at them. Data inputs used in response to the four research questions are further presented orderly in this section. In Section 3, the study results are first presented for three intermediate data categories (land areas, populations, and heat demands), according to their respective distribution by five different classes of heat densities among the 28 member states (e.g. in Appendix tables). In four succeeding subsections, again corresponding to the four research questions posed, the result section then presents the findings regarding physical and economic suitability, regarding current deployment levels of district heating and found levels of economic suitability, and eventually gives a simple answer to why district heating also can be a viable option in some Mediterranean countries. In Section 4, the study findings are discussed with focus on reduced future heat demands, key study assumptions, the two used suitability concepts; and the possibility of elaborating these concepts further in future studies. Finally, the main conclusions in Section 5 present concentrated answers to the four study research questions.

2. Materials and methods

The main improvements for the application of the distribution capital cost model in this work, compared to Ref. [14], consist in an extended extent (28 countries compared to 83 cities in four countries), an extended scope (national heat markets compared to city heat markets), and in a homogenous spatial form of representation (uniform hectare grid compared to heterogeneously shaped city districts). The main working tool in order to facilitate these improvements has been GIS software, e.g. the ArcMap Spatial Analyst extension, where the tools Raster Calculator (calculating cost parameters based on densities), and Zonal Statistics (summaries by density classes and member states) have been used for the implementation of study formulae and calculations. In terms of format, hectare grid raster GIS datasets were used for all suitability parameters, all of which were provided in a common INSPIRE-compatible spatial reference system, while likewise compatible vector polygon GIS datasets were used for aggregation by e.g. NUTS3 regions and member states. Additionally, a more elaborated approach to assess service sector building heat demands is used here compared to the simple average statistics-based factor of 1.4 relative to the identified residential sector building heat demands in the original work.

In terms of data, a fundamental problem for the assessment of heat density and investment costs for district heating in a European context is the simple fact that no such data is directly available. This is itself one of the main challenges in this work and we have solved this challenge by adapting our methodical approaches so that other datasets, publicly accessible and initially perhaps intended for other objectives, can be utilised for the purposes at hand. The presented assessments may therefore be said to be data-driven and based on existing data when possible and when not, based on exploratory multilinear regression modelling (OLS) that uses already mapped phenomena. If this principle conduct itself may be regarded as a novelty in theory and method, it is for its viability and success absolutely reliant on the efforts and the devotion whereby the European community manages to provide such datasets. In this respect, appropriate credit and acknowledgement should be given to e.g. Eurostat [22], the European Environmental Agency [23], the EU Joint Research Centre [24], as well as to specific European Union initiatives and programs for developing valuable guidelines and datasets for useful research purposes (e.g. Inspire [25,26], the Urban Audit [27], Corine [28], and several others).

As for the methodological accounts to be given here, the focus is exclusively on key features and elements regarding the methods, approaches, and assumptions whereby the two suitability metrics were established. The reason for this is that detailed accounts already have been given and it would be superfluous to repeat these here (see e.g. Refs. [29,30] for physical suitability and references [14,30–32] for economic suitability). As the following subsections thus are devoted essentially to principal methodical aspects concerning the two metrics at hand, the unfamiliar reader is recommended to consult these references for complementary accounts.

2.1. Heat demand density (physical suitability)

The density of building heat demands may be assessed in several different ways. One approach is to use georeferenced data on buildings from national building registers (if available) combined with data on building stock characteristics (such as average heat demand per square meter floor area and year). In the Danish heat plan projects of 2008 and 2010 [33,34], which may be regarded as pioneering efforts in the charting of heat demand distributions on national scale, this approach facilitated highly detailed mapping of the Danish building heat market. A similar approach is also applied in the current Hotmaps project [35]. An alternative source of georeferenced building data (if national building registers are not available) may be found in the use of photogrammetry technologies (aerial photo). In Germany, Der Energieeffizienzverband für Wärme, Kälte und KWK e.v. (AGFW) initiated such studies already in 2010, which managed to render highly detailed assessments of heat densities thus based on measurements retrieved from remote sensing [36]. Currently, LiDAR (Light Detection and Ranging) data are increasingly also being used to add volumetric building data.

Another source of information whereby to assess spatial distributions of settlements, likewise depending on remote sensing, is that of interpreted satellite imagery. In the first ever estimate of the physical suitability for district heating on a European scale, Gils et al. [37] (see also for the USA [38]) relied in 2012 on population density and land use data produced by such methods [28,39,40], combined with energy statistics on energy use in buildings. Prior to this, remote sensing techniques had been used inter alia by Kazenko et al. to analyse the compactness of urban areas [41], and by Sen, when already in 2004 emphasising the importance of a strong remote sensing regime in contemporary national and international energy policy [42]. In parallel, Geiss et al. used a remote sensing approach for the characterisation of settlement structures to assess local potentials for district heating [43], a deliberate heat market focus that emerged also in several other spatial-oriented studies at the time [44–48], and more recently applied in combination with e.g. fuzzy logic [49].

Principally, the concept of heat density, q_L (J/m^{2}a), may be expressed as the product of the population density, p (n/m^2), the total building space per capita, α (m^2/n), and the specific heat demand for buildings, q (J/m^{2}a), or the product of the population density and the heat demand per capita, q_P (J/n,a), as in Eq. (1):

$$q_L = p \cdot \alpha \cdot q = p \cdot q_P \left[\mathrm{J} \big/ \mathrm{m}^2 \mathrm{a}\right] \tag{1}$$

It is evident by the nature of the three factors in this expression, that the product may be established in various ways depending on how the factors themselves are produced. Population density, for example, may alternatively be assessed for any given land area by dividing its total building space (floor area, if known) with the specific building space number for that area. This may serve as an indication of the multiplicity of approaches whereby heat density can be determined. However, one distinct division needs to be made with reference to residential heat demands density, which principally adheres to population density distributions, and that of service sectors heat density, which cannot be represented on the same basis.

In this work, the first step to assess the physical suitability for district heating has been to develop and use exploratory multilinear regression models to determine residential and service sector floor areas on hectare level for all of EU28. For the residential sector, referring here to all buildings where people live, single-family house (SFH) floor areas and multi-family house (MFH) floor areas were modelled separately, utilising as independent variables the hectare grid cell data from the European Settlement Map on built-up coverage [50], the Global Human Settlement Layer population grid of the EU Joint Research Center [51], and the degree of soil sealing layer from the European Environmental Agency [52]. For service sector floor areas, referring here to all non-residential buildings with the exclusion of industries, the above and also the square kilometre grid data on gross domestic product (GDP) of the United Nations Environment Program was used as a measure of economic activity [53].

In the second step, residential heat densities, $q_{L,res}$ (J/ha), were established by utilising the modelled floor areas together with population and housing census data on specific building spaces per dwelling type [54], to determine the number of people living in single, $P_{ha,SFH,c}$ (n/ha), vs. multi-family houses, $P_{ha,MFH,c}$ (n/ha), for each hectare grid cell (total cell population counts corrected by use of [51]). Subsequent summation on member state level rendered total national population counts per dwelling type ($P_{tot,SFH}$ (n) and $P_{tot,MFH}$ (n)), which together with total member state heat demand data by dwelling type ($Q_{res,SFH}$ (J) and $Q_{res,MFH}$ (J)) [12], allowed the proper distribution of the latter in proportion to each grid cell, as expressed in Eq. (2). In a final step, all distributed grid cell values were multiplied with a climate and population concentration correction factor, $NHI_{N3R,WAM}$, reflecting NUTS3 region values of the European Heating Index [55], to render residential sector heat density.

$$q_{L,res} = \left(\frac{P_{ha,SFH,c} \cdot Q_{res,SFH}}{P_{tot,SFH}} + \frac{P_{ha,MFH,c} \cdot Q_{res,MFH}}{P_{tot,MFH}} \right) \cdot NHI_{N3R,WAM} \ [\mathrm{J/ha}] \tag{2}$$

For service sector heat density, the modelled floor areas, $A_{floor,ha,ser}$ (m^2/ha), were used together with NUTS3 regional (N3R) service sector heat demand data, $Q_{ser,N3R}$ (J), established on the basis of national heat demand data, regional population counts and the European Heating Index, and regionally distributed service sector floor areas, $A_{floor,N3R,ser}$, (m^2), according to:

$$q_{L,ser} = \frac{Q_{ser,N3R} \cdot A_{floor,ha,ser}}{A_{floor,N3R,ser}} \ [\mathrm{J/ha}] \tag{3}$$

Finally, by addition, the sum of the residential and service sector building heat densities in a given hectare grid cell represents the final measure by which its physical suitability for district heating may be determined. Noteworthy, these heat densities reflect statistically derived total volumes which only implicitly take into consideration contextual effects such as urban heat islands. The effect of the latter, an occurrence resulting in somewhat reduced heat demands in the most dense areas, is not allocated in this work. The significance of not doing so should however be minor since these, the most dense areas, simultaneously have the lowest heat distribution costs. Likewise, mixed-use building characteristics (both residential and service sector use) are accounted for only implicitly by separate spatial mapping of each sector respectively. By use of five characteristic class levels of heat density, elaborated by inspiration from Ref. [56], the degree of physical suitability for district heating may then be distinguished for each hectare cell as well as summarised in aggregates, as outlined in Table 1.

Table 1
Physical suitability for district heating by classification of five heat density classes.

Heat density class	Heat density intervals [MJ/m^2]	Concentration of heat demands
0	0	No modelled heat demand
1	$0 < q_L < 20$	Very sparse
2	$20 \le q_L < 50$	Sparse
3	$50 \le q_L < 120$	Moderate
4	$120 \le q_L < 300$	Dense
5	$q_L \ge 300$	Very dense

2.2. Distribution capital cost (economic suitability)

The economics of district heat distribution was at the time of publishing the original paper [14], and has principally so remained, an area of academic study with quite few reported investigations. Although the original paper has been cited in the years that have passed since, most of these citations have referred essentially to basic premises and principal conclusions from that work (see for example refs. [57–69]), and less so to the explicit distribution cost metric. A few studies, however (to our current knowledge), have since presented examples of heat distribution cost assessments [70–72], while some others have referred to the specific investment cost of district heating in more general terms [73–76].

The marginal distribution capital cost, C_d (euro/GJ), or the specific investment cost, for district heating, expresses the annuitized (annuity factor: a (–)) payback on investment capital for the heat distribution piping system buried into the ground, I (euro), by the annual volume of heat sold to the connected heat customers, Q_S (GJ), as expressed in Eq. (4) [10]:

$$C_d = \frac{a\cdot I}{Q_S} = \frac{a\cdot\left(\frac{I}{L}\right)}{\left(\frac{Q_S}{L}\right)}\ [\text{euro/GJ}] \tag{4}$$

By introducing the total pipe trench length, L (m), the denominator term Q_S/L denotes linear heat density (GJ/m), i.e. annual heat sales by trench route meter, the transformation of which was the ultimate objective when the heat distribution capital cost model was first conceived and developed. The transformation of the traditional expression of linear heat density aimed for its substitution the utilisation of statistically available parameters (independent of the existence or not of current district heating systems), thus converting the empirical expression into an analytical model. The substitution consisted in the introduction of four new data parameters: population density, specific building space, specific heat demand (all of which are represented in Eq. (1)), and effective width, w (m), as expressed in Eq. (5):

$$C_d = \frac{a\cdot\left(\frac{I}{L}\right)}{p\cdot\alpha\cdot q\cdot w} = \frac{a\cdot\left(\frac{I}{L}\right)}{e\cdot q\cdot w} = \frac{a\cdot(C_1 + C_2\cdot d_a)}{q_L\cdot w}\ [\text{euro/GJ}] \tag{5}$$

Hereby, linear heat density may be found as the product of heat density and effective width, while the specific investment cost (I/L) may be derived empirically as a linear function with intercept C_1 (construction cost constant (euro/m)), and the slope determined by multiplication of C_2 (construction cost coefficient (euro/m^2)) and the average system pipe diameter, d_a (m). As can be seen in Fig. 2, construction costs were established for three characteristic area categories: (A) Inner city areas, (B) Outer city areas, and (C) Park areas, where after an adapted average function on the basis of these three categories was assessed for pipe diameters up to 0.3 m. For this study, construction costs, which in Ref. [14] were based on 2007 Swedish cost catalog values, were updated by use of a Swedish entrepreneur index [77–79] to represent average 2015 cost levels (currency exchange rate 9.36 SEK/euro [80]). The rationale for this conduct is that no newer construction cost data has been published since, why the index (reflecting the general cost development in Swedish industrial activities) was used a proxy for the increase in district heating construction costs during the given time period. Hereby, an average construction cost constant value of 212 euro/m and an average construction cost coefficient value of 4464 euro/m^2 is used uniformly for all considered hectare grid cells as representative of average current construction cost conditions in Europe.

Additionally, the product of population density and specific building space constitute the plot ratio, e (–), which expresses the ratio of building space area per given land area. In this study, plot ratio values were established for each hectare grid cell based on floor area data and used to determine the corresponding effective width value, according to an adaption of their relationship as presented in previous studies [32], and as outlined in Eq. (6):

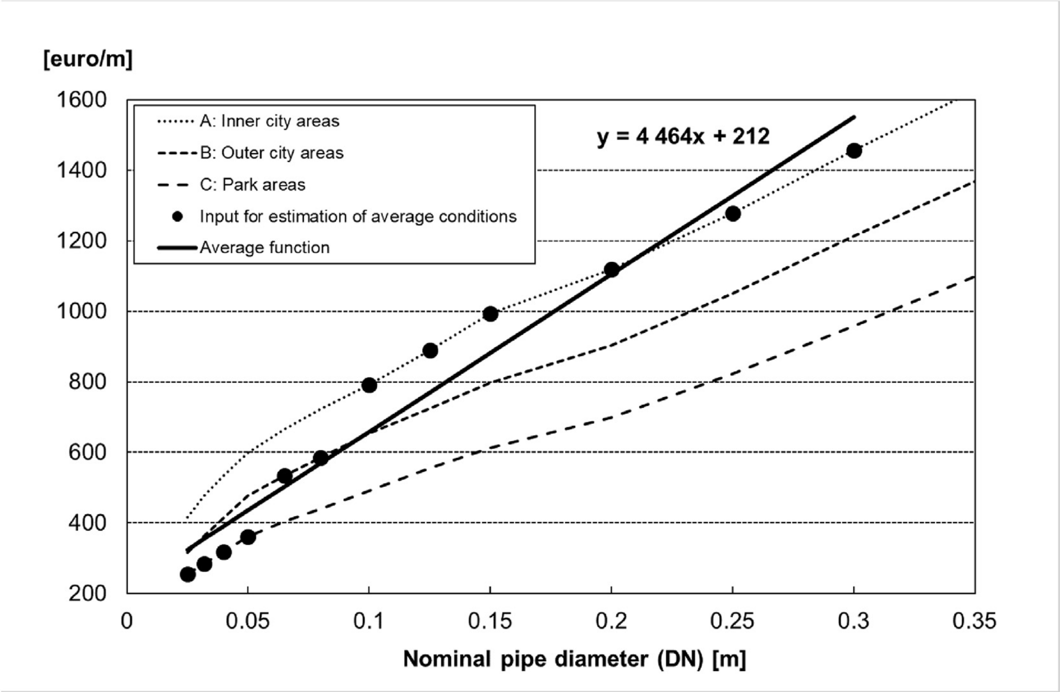

Fig. 2. Average construction cost function based on assessed 2015 investment costs for district heat distribution systems for three characteristic area categories: (A) Inner city areas, (B) Outer city areas, and (C) Park areas. Sources: [77–80].

$$0 < e \le 0.4; w = 137.5 \cdot e + 5, e > 0.4; w = 60 \text{ [m]} \tag{6}$$

For the assessment of pipe diameters, the logarithmic relationship between linear heat density and average pipe diameter established in the original paper, was used here unaltered (Eq. (7)). In the calculation of pipe diameters, a lower limit of linear heat densities at 1.5 GJ/m was set. Below this threshold, pipe diameters of 0.02 m were applied uniformly for all hectare grid cells with present heat density values above zero.

$$d_a = 0.0486 \cdot ln\,(q_L \cdot w) + 0.0007 \text{ [m]} \tag{7}$$

An annuity factor (a) of 0.051, based on 30 years investment lifetime and a real interest rate of 3%, was chosen to reflect a long term investment strategy to obtain the benefits of district heating in the future. Hereby, input values for all the elements in the distribution capital cost model were established. The model output, the distribution capital cost in a given hectare grid cell, represents the final indicator by which the economic suitability for district heating may be determined. Economic suitability, however, is, contrary to physical suitability, not subject for characterisation by class levels in this context. This is due to the fact that capacities for district heating investments, and whatever cost levels may be considered acceptable or not, are determined by the unique circumstances of each single case. For this reason, economic suitability is displayed in this paper as cumulative cost curves reflecting attainable relative shares for district heating on total heat markets at corresponding cost levels.

2.3. *Comparison with current deployment levels*

To facilitate a comparison of current member state deployment levels of district heating with relation to the economically suitable levels anticipated in this study, the comprehensive heating and cooling demand profile dataset developed in work package 3 of the Heat Roadmap Europe project was used. From this dataset, publicly available at [81] and further documented in Ref. [12], national average heat market shares for district heating was derived for the year 2015.

2.4. *Aggregated explanation for physical suitability*

The background for the fourth research question is that a widespread perception appears in Europe that district heating is only viable in cold areas as the North European countries. In order to rebut this perception, we will provide a simple answer in just one diagram containing combinations of annual heat demands per capita and population densities for the three most dense heat density classes. Each national input for this diagram and the corresponding heat density appears in the right columns in Table A3.

3. Results

The results emanating from this work are manifold, both in terms of character and mode of representation. It should be kept in mind that the fundamental rationale behind this study has been the identification of unique local conditions, and the subsequent evaluation as of the suitability for district heating in each hectare grid cell of all 437 million hectares constituting the EU28 land area.

Since the results to be accounted for here refer to aggregates, the reader is urged to consult the Pan-European Thermal Atlas (PETA), i.e. the publicly available Heat Roadmap Europe map application [82]. At this website, both suitability metrics may be viewed in their full geographical extent as operational layers superimposed on selectable base maps of the European continent.

In the following, the results of the study are presented in analogy with the four research questions posed in the introduction section. As for the certainty of the presented results, it must be noted that these all relate to a GIS model of the 2015 heat density distributions of the EU28 member states, not on actual measurements at each location. For this reason, examples of local real-world deviations from the modelled cases are to be expected, especially so for some edge grid cells which may not have been properly identified by corresponding member state ID in the zonal statistics operations.

Land areas, populations, and heat demands in each member state are presented by the five applied heat density classes in Tables A1–A3., respectively. These tables have been established on the basis of zonal statistics performed within the used geographical information system. The aggregated information for EU28 including average population densities, average heat densities, and average heat demands per capita is provided in Table 2. Heat density classes' 3–5 capture mainly high concentrations of heat demands in towns and cities. According to Table 2, 78% of the total heat demand in buildings are located in the three most dense heat density classes that constitute 1.4% of the total land area and 70% of the population. It is in these areas that district heating can find its prospective customers.

3.1. *Physical suitability*

Concerning the land area of EU28, it amounts to 4.37 million square kilometres, according to Eurostat land use data for 2015 [83]

Table 2

Aggregated information for EU28 concerning land areas, populations, and heat demands distributed by the five applied heat density classes. All information relates to 2015.

Heat density class	5	4	3	2	1	0	Total
Heat density intervals, MJ/m^2	>300	120–300	50–120	20–50	<20	zero	
Land area, thousand km^2	4.81	16.3	41.8	42.6	297	3967	4370
Population, million	65.2	114	175	80.0	60.4	13.5	509
Heat demand, EJ/a	2.20	3.00	3.21	1.40	0.97	0	10.8
Average population density, n/km^2	13,559	7018	4189	1877	203	3	116
Average heat density, MJ/m^2	458	184	77	33	3	0	2
Heat demand per capita, GJ/a	33.7	26.2	18.3	17.5	16.0	0	21.2
Proportion of land area	0.1%	0.4%	1.0%	1.0%	6.8%	90.8%	100%
Proportion of population	12.8%	22.5%	34.4%	15.7%	11.9%	2.6%	100%
Proportion of heat demand	20.4%	27.9%	29.7%	13.0%	9.0%	0%	100%
Accumulated proportion of land area	0.1%	0.5%	1.4%	2.4%	9.2%	100%	
Accumulated proportion of population	12.8%	35.3%	69.7%	85.5%	97.4%	100%	
Accumulated proportion of heat demand	20.4%	48.3%	78.0%	91.0%	100%	100%	

and as summarised in Table 2. When studying the land area distributions by heat density classes in Table 2, it is clear that only 9.2% of the EU28 land area hosts residential and service sector buildings with corresponding presence of heat demands. If further disregarding the 6.8% represented by the very sparse heat density class consisting of purely rural areas, and the 1.0% semi-rural areas land area assigned to the sparse heat density class, the remaining 1.4% represent urban land areas with moderate, dense, and very dense conditions.

National conditions in terms of land areas with presence of building heat demands, as outlined in Table A1., reveal that most member states align fairly well with the EU28 average value although some significant member state deviations are present, for example Finland (~2%), Sweden (~3%), and Spain (~3%). Significant deviations are also present with respect to the opposite case, where e.g. Malta (54%), the Netherlands (29%), and Belgium (22%), represent member states with very high proportions of land areas designated to residential and service sector buildings.

Concerning the EU28 population, it was 509 million at the end of 2015 according to Table 2. According to our estimations, only 13.5 million, or 2.6%, live in areas without buildings or heat demands. Hence, this estimation can be apprehended as the estimation error in our method since these heat demands, due principally to geographic resolution issues, have not been allocated in our GIS analysis. If focussing only at heat density classes with appropriate physical suitability levels for district heating (i.e. moderate, dense, and very dense conditions), a population of 355 million inhabitants live within these three dense classes. It is also evident from Table 2 that the population densities are very high in these dense heat density classes.

National conditions can be obtained from Table A2 where national differences in typical settlement structures are implicitly visible. Several member states appear to have relatively high shares of population counts located in moderate (3) and dense (4) heat density classes, but significantly less so in the highest class (5). This is the typical case for member states such as e.g. the Netherlands (40%, 49%, and 3%), the United Kingdom (70%, 16%, and 2%), and Bulgaria (23%, 25%, and 3%), which indicate preferences for single-family housing, albeit in highly densified residential areas. The reversed case, where the preference within the top-three high heat density classes appears to be that of multi-family housing and dedicated urban settlement structures, seems to be the order in member states such as Latvia (13%, 20%, and 27%), Spain (20%, 30% and 24%), and Italy (22%, 30%, and 21%).

Concerning heat demand in EU28 during 2015, it was 10.8 EJ according to Table 2. A profound observation is that 5.2 EJ is situated within the dense and very dense heat density classes, meaning in principal that half of this heat market exhibits strong physical suitability for district heating. The heat demands per capita are also much higher in the more dense areas, since most service sector buildings are located in these areas. In Fig. 3, the detailed distribution of the heat demand and the population proportions are presented by proportions of land area for the whole EU28. At the lowest proportion of land area presented, the proportion of heat demands is ten times higher than the proportion of population. By descending heat densities, the accumulated heat demand proportion is always situated above the accumulated population proportion, again revealing that the heat demands are concentrated to areas with high heat densities.

National conditions for heat demands can be identified in Table A3. Germany (~2.4 EJ), France (~1.6 EJ), the United Kingdom (~1.4 EJ), and Italy (~1.3 EJ), represent by far the four largest national heat markets in terms of annual demand volumes. The national heat demand proportions with respect to heat density classes are also visualised in Fig. 4, by descending order of the proportion of heat demands in the very dense class. If summing up the proportions for classes 3–5, some member states reach totals well above the EU28 average, such as the Netherlands (90%), the United Kingdom and Luxembourg (both at 89%), and Germany (86%), while some others are well below this level, such as Cyprus (11%),

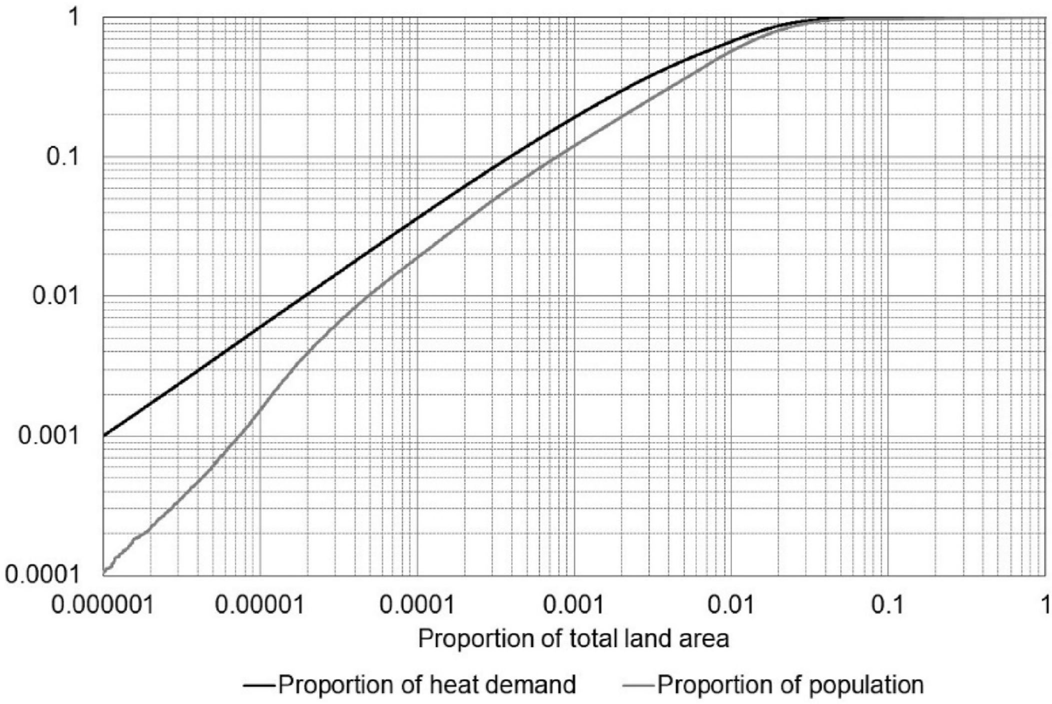

Fig. 3. Proportions of EU28 heat demands in buildings and population by proportion of total land area and by descending order of heat density. Hereby, high heat densities appear to the left in the diagram and low heat densities appear to the right.

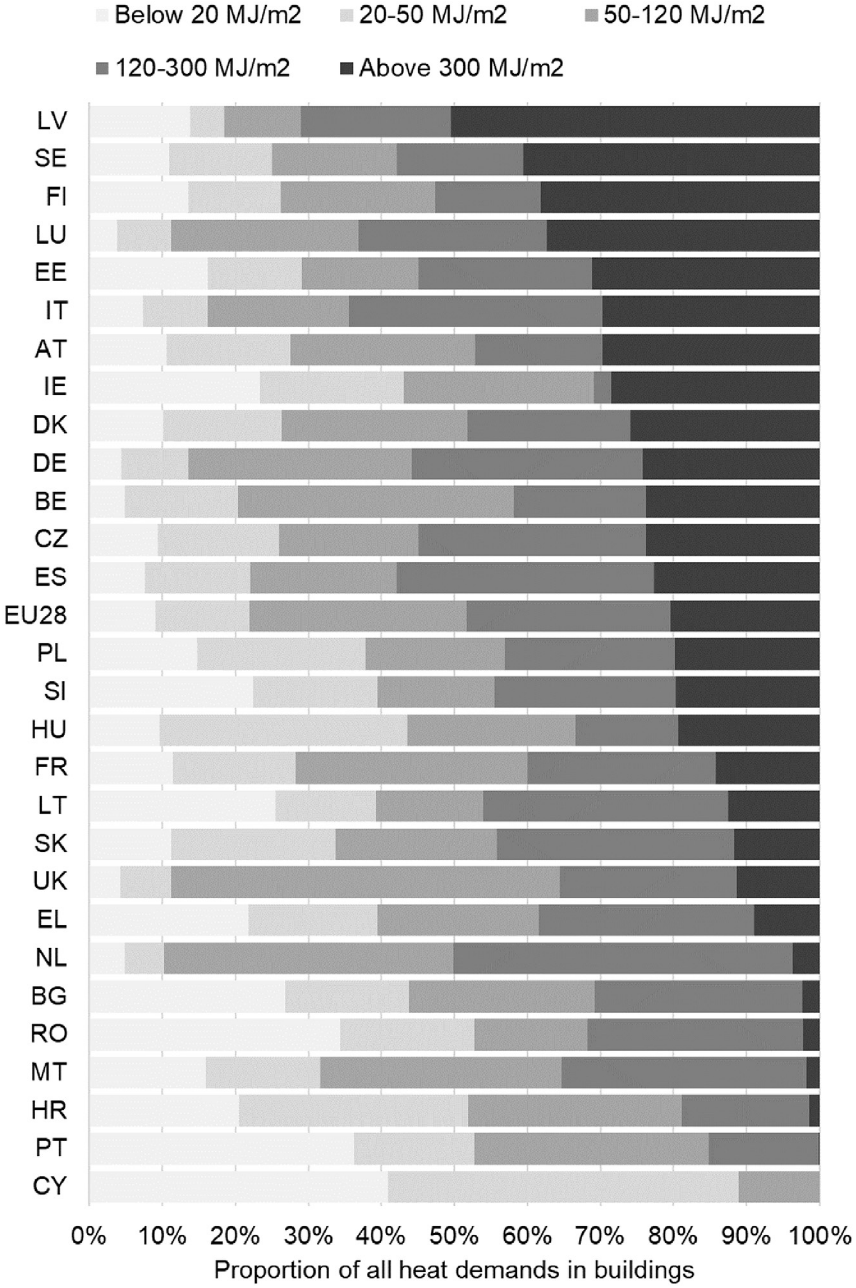

Fig. 4. Proportions of national heat demands by the five heat density classes applied and sorted according to the proportion of heat demands in the most dense heat density class.

Portugal (47%), and Romania (47%). If considering the two top classes (4 and 5) only, member states like Latvia (71%), Italy (64%), and Sweden (58%) provide indications of very high proportions of total national heat demands within these two demand segments.

3.2. *Economic suitability*

The final result output regarding found economic suitability levels for district heating in each member state are in the following presented in four graphs (Fig. 5, Fig. 6, Fig. 7, and Fig. 8), which are all designed in allegory with those presented in the original paper [14]. This means that after summation of all hectare grid cell heat demands possible to satisfy at each corresponding distribution capital cost level, these have been consecutively sorted from the lowest to the highest and then plotted with respect to the corresponding national heat market shares that they represent. This modelling, for which a 100% connection rate to district heating networks have been generally assumed, has been based on the methodology and input data accounted for above, and distinguishes further between the marginal distribution capital cost, as established in Eq. (4) and Eq. (5), and the average distribution capital cost, $C_{d,a}$. This latter cost metric expresses the quota of accumulated investment costs by accumulated heat demands for each marginal distribution capital cost level.

The overall resulting distribution capital cost curves, marginal as well as average, for EU28 are shown in Fig. 5. By the grand total curve for the marginal distribution capital cost, which is included for reference also in the following graphs, we do recognise the general line characteristic of that found in Ref. [14], i.e. a levelling-out tendency in the lower heat market share segment. However,

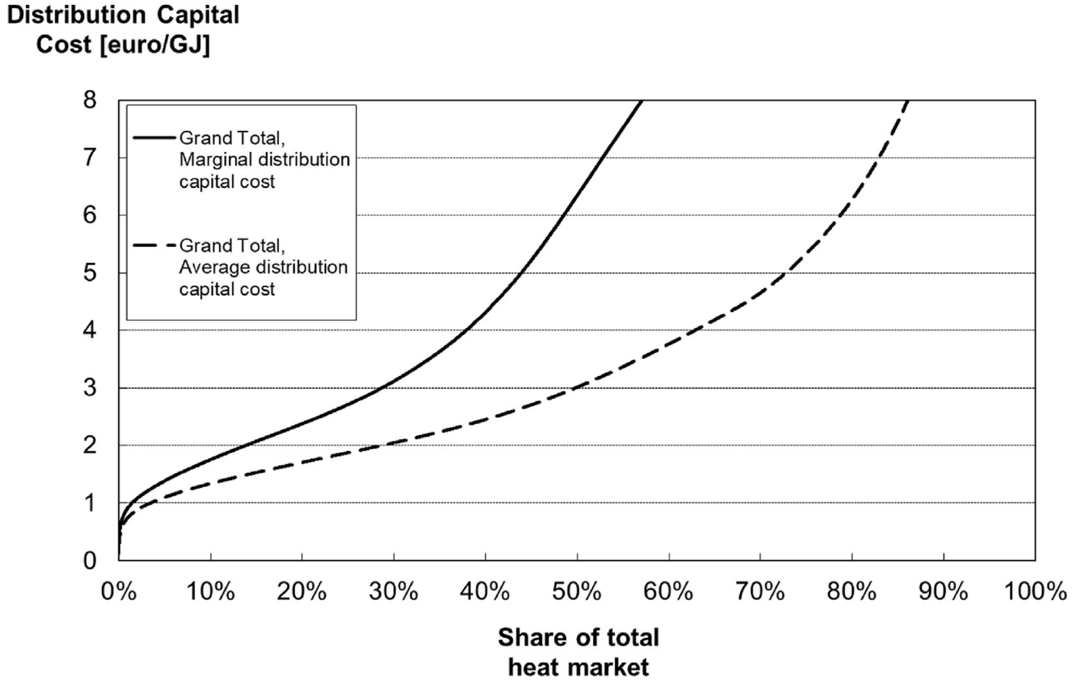

Fig. 5. Current distribution capital cost levels and the corresponding district heat market shares in EU28 on average.

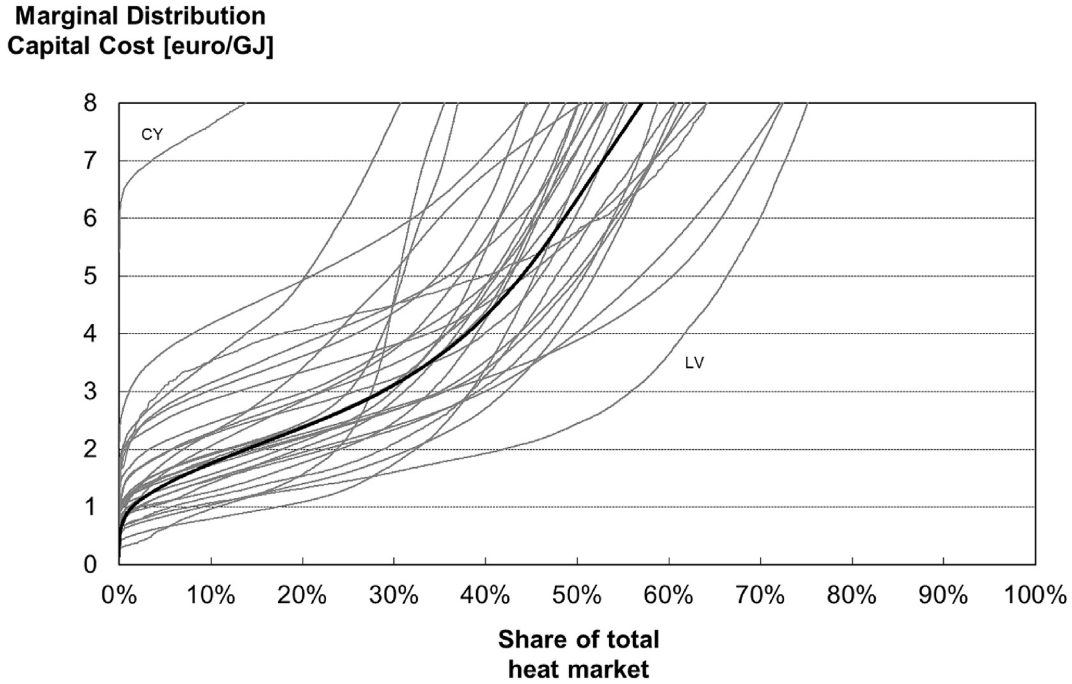

Fig. 6. Current marginal distribution capital cost levels and the corresponding district heat market shares in the EU28 member states.

since total national heat markets constitute the reference in this study (not just a few randomly selected urban heat markets as in the original work), this tendency is less pronounced here, and also less extensive.

If, by reference to the 48% heat demand share found in dense and very dense heat density classes, as presented in Table A3., half of the EU28 building heat market were to be supplied by district heat, this would imply marginal investment costs in the order of 6.34 euro/GJ, corresponding to average cost levels of 3.01 euro/GJ. With reference to the current average EU28 heat market share for district heating (~12%), market expansions up to 30% (~3.08 euro/GJ, marginal cost) are associated with less rapidly increasing specific investment costs, compared to those appearing above this heat market share, and average EU28 district heat market shares above 60% must be deemed hardly, if at all, feasible.

To better understand the varying conditions of economic

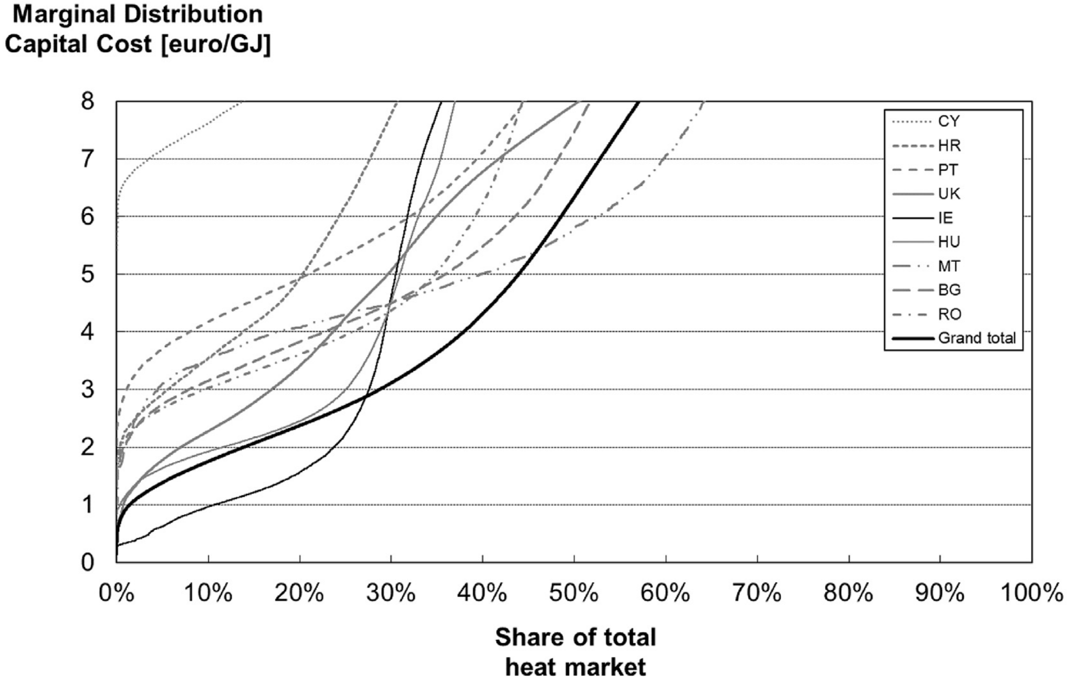

Fig. 7. Current marginal distribution capital cost levels and the corresponding district heat market shares in the nine member states with marginal distribution capital cost levels above 4.0 euro/GJ at 30% market shares (low economic suitability).

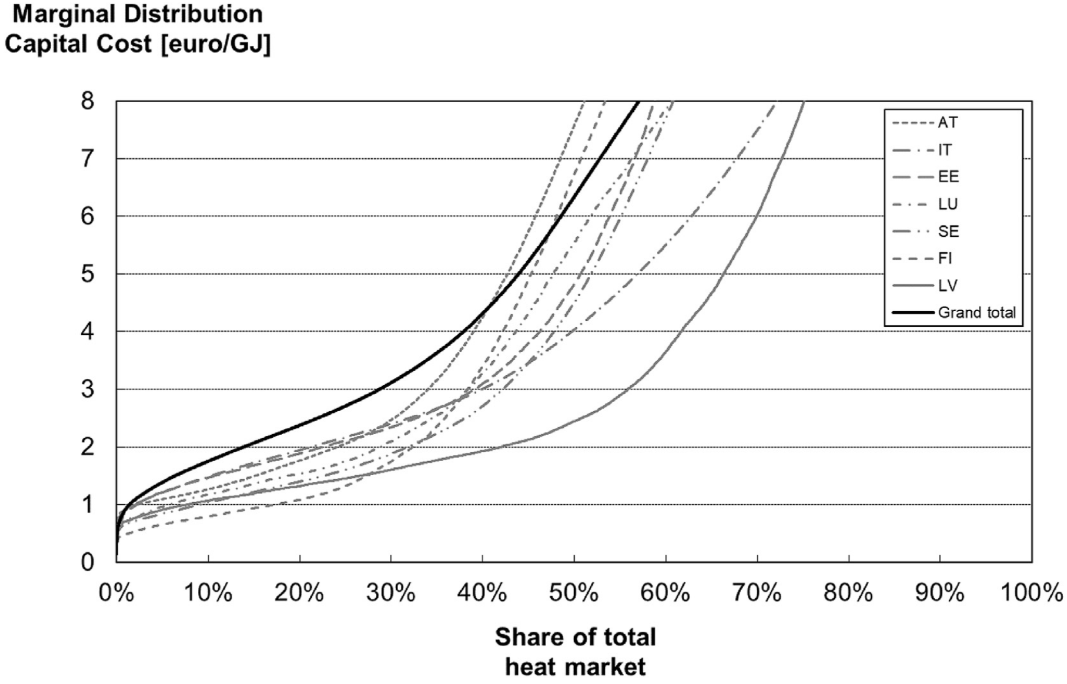

Fig. 8. Current marginal distribution capital cost levels and the corresponding district heat market shares in the seven member states with marginal distribution capital cost levels below 2.5 euro/GJ at 30% market shares (high economic suitability).

suitability for district heating among the 28 member states, Fig. 6 depicts national cost curves for the marginal distribution capital cost. Here, the full spread of such varying conditions are delimited by the two extremes found in the data. On the on hand, Cyprus exemplifies poor economic suitability conditions due, principally, both to low levels of population concentrations as well as of low levels of annual heat demands. At the other end of the spectrum, Latvia illustrates highly favourable economic suitability conditions, resulting from both high levels of population concentrations as well as of considerable annual heat demands, resulting in a conceivable 70% national heat market share for district heating at marginal cost levels well below 6.0 euro/GJ.

The spectrum of poor versus favourable economic suitability conditions for district heating may be further exposed if from the study population extracting those member states that are most representative of each respective category. Thus, Fig. 7 shows the extraction of those nine member states which all were found to have marginal distribution capital cost levels above 4.0 euro/GJ at 30% district heating heat market shares (low economic suitability). With the exception of Ireland, which indeed exhibit very favourable economic suitability up to heat market shares of approximately 25%–30%, district heating expansions in most of these member states are, in general, likely to be associated with higher specific investment costs compared to average EU28 conditions.

In Fig. 8, a comparative extract of those seven member states which all were found to have marginal distribution capital cost levels below 2.5 euro/GJ at 30% district heat market shares (high economic suitability) is presented. Here, Austria, Italy, and Luxembourg, exhibit similar high economic suitability conditions as those found in two Nordic (Sweden and Finland) and two Baltic (Estonia and Latvia) member states.

Noteworthy, it should be underlined in this respect that the aggregated accounts outlined in Figs. 6, Figs. 7 and 8, certainly provide indications with regards to general, national level, conditions of economic suitability for district heating, while, however, the true merit of the study results are their identification and representation of genuine, local conditions. This merit is exemplified for the urban area of the Danish city of Aalborg in Fig. 9. Likewise, possible deviations in the outputs may be due to the use of Swedish construction cost levels, generalised for the purpose of continental mapping and further reflecting mature district heating market conditions which may be lower than those occurring on novel markets, and as well the chosen exchange rate SEK/euro. In terms of economic suitability, further, specific investment costs

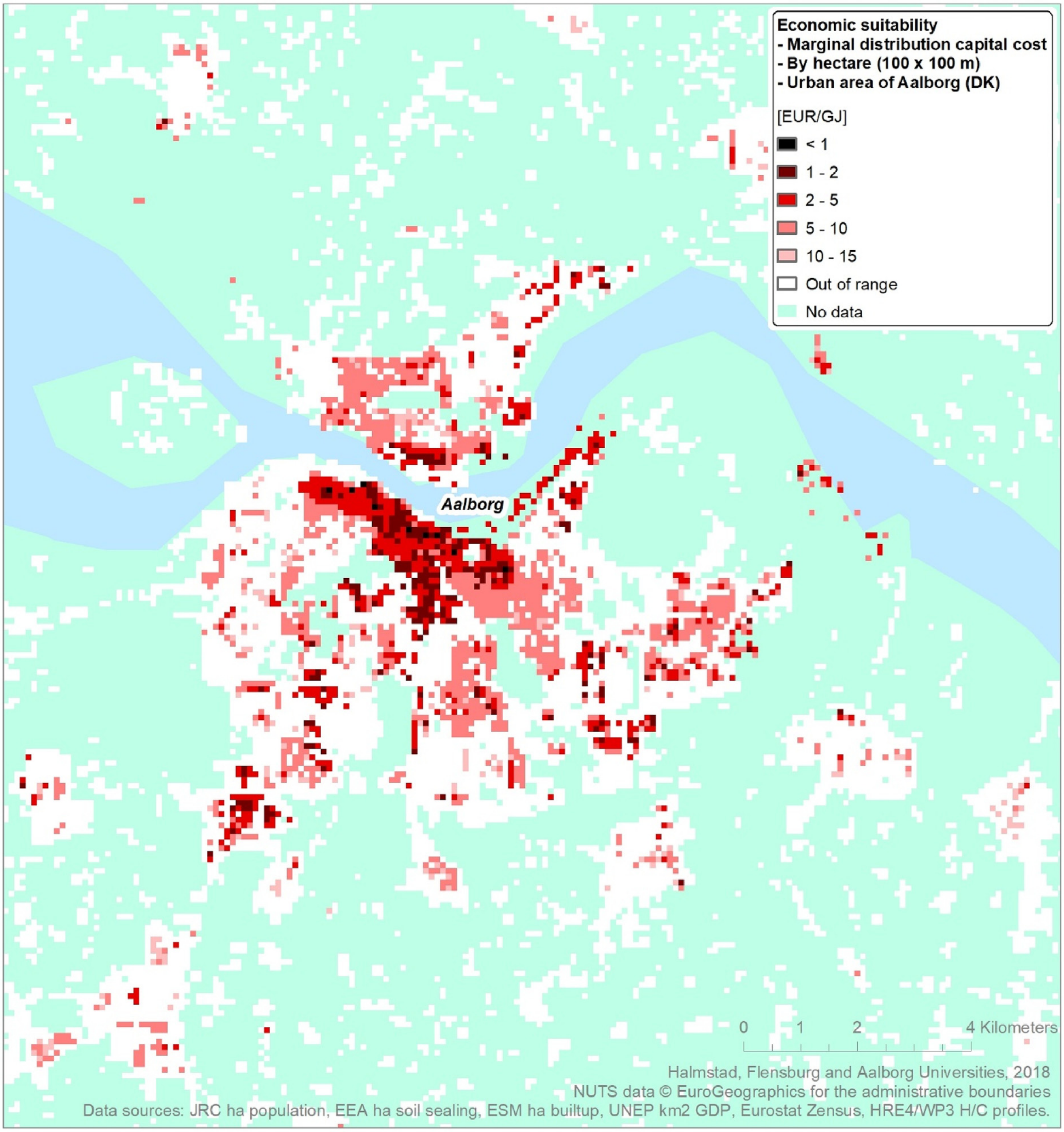

Fig. 9. Economic suitability for district heating by marginal distribution capital cost at hectare level for the urban area of Aalborg, Denmark.

have here been assessed by use of an average linear cost function (as presented in Fig. 2), which inevitably implies a certain degree of generalisation.

3.3. Comparison with current deployment levels

As for the issue of how current deployment levels of district heating in the EU28 member states relate to the levels assessed here as economically suitable, the study findings are presented in Table 3. By economically suitable, a conservative approach has been chosen here thus considering a heat market saturation as applicable only with reference to the top-two heat density classes, i.e. dense (4) and very dense (5). From the above, further, we know that this equates approximately to a total EU28 annual heat demand volume of 5.2 EJ (48%, Table A3.), to a total population count of some 180 million (35%, Table A2.) and to some 21 thousand square kilometres out of the total EU28 land area (0.5%, Table A1.). We further know from Fig. 5 that an average EU28 district heating heat market share of 50% under current conditions would correspond to a marginal distribution capital cost of 6.34 euro/GJ, a cost level which therefore has been used as a saturation benchmark when expanding district heating on the 28 national heat markets.

It can be seen in Table 3 that, when applying the general EU28 benchmark condition for an average 50% heat market share (6.34 euro/GJ, marginal distribution capital cost, corresponding to 3.01 euro/GJ, average distribution capital cost), the feasible expansion limit of district heating differ on different national heat markets. If for the moment ignoring Cyprus (which due to no reported presence of district heating at current is a non-representative case), these differences range from 26% (Croatia) to Latvia (71%), and are quite dispersed in general.

If further assessing the expansion characteristics from current levels, as stipulated by this level of saturation, an average EU28 expansion factor for district heating is found at approximately four times current levels, while two member states (Denmark and Lithuania) already at present have deployed district heating beyond this level of saturation. From this, the monetary value in terms of total investment costs, if expanding district heating on all national heat markets to its full saturation level, corresponds to 269 billion euro (2015).

If selecting, finally, those member states with largest expansion potentials in terms of annual heat demand volumes, thus in an attempt to pinpoint the most substantial expansion markets for district heating in EU28, the eight member states presented in Fig. 10 and assembled in Table 4 is the result. Together these eight member states represent 89% of the total expansion investment volume and 90% of the total expansion heat demand, at an average expansion factor of 30. Note also that national marginal distribution capital costs curves, as well as additional information, for these selected member states are given in the country reports (Heat Roadmaps) associated with [84].

3.4. Aggregated explanation for physical suitability

Combinations of national averages of the annual heat demand per capita and population densities are provided in Fig. 11 for the three most dense heat density classes. Products of these two averages generate the national average heat densities for these heat

Table 3

Current and saturated deployment levels of district heating (DH) for residential and service sector buildings in the EU28 member states with corresponding average distribution capital costs and total investment costs (I). The saturated deployment level corresponds to a common average EU28 market share of 50% at marginal distribution capital cost of 6.34 euro/GJ.

MS	Current situation (2015)				Saturated (EU28, 50% average)			
	DH [PJ/a]	DH [%]	Average distribution capital cost [euro/GJ]	I [billion euro]	DH [PJ/a]	DH [%]	Average distribution capital cost [euro/GJ]	I [billion euro]
AT	65	28%	1.5	1.88	109	47%	2.4	5.2
BE	5	2%	1.1	0.11	137	42%	2.6	7.1
BG	17	25%	3.3	1.11	31	45%	4.1	2.5
CY	0	0%	–	0	0.02	0%	6.1	0.0
CZ	68	29%	1.9	2.59	133	56%	2.9	7.6
DE	264	11%	1.5	7.60	1339	56%	2.9	76.9
DK	95	58%	3.7	6.92	76	47%	2.7	4.0
EE	15	45%	2.1	0.61	19	55%	2.6	0.9
EL	2	1%	1.6	0.05	55	47%	3.5	3.7
ES	2	0.5%	1.0	0.04	328	67%	3.1	20.0
FI	107	47%	1.8	3.86	111	49%	2.0	4.3
FR	81	5%	1.2	1.98	669	43%	3.2	41.4
HR	7	10%	2.9	0.38	17	26%	4.0	1.3
HU	27	13%	1.7	0.88	71	34%	2.7	3.7
IE	1	1%	0.3	0.00	34	32%	1.7	1.1
IT	51	4%	1.0	0.98	828	65%	2.9	46.9
LT	24	52%	3.3	1.54	23	51%	3.2	1.5
LU	3	13%	1.0	0.07	14	53%	2.4	0.7
LV	23	50%	1.5	0.67	33	71%	2.2	1.4
MT	0	0%	–	0	2	55%	4.4	0.1
NL	21	5%	2.3	0.95	230	54%	3.9	17.4
PL	206	31%	2.2	8.85	304	46%	2.9	17.3
PT	1	2%	2.9	0.07	22	35%	4.7	2.0
RO	42	23%	3.0	2.48	74	40%	3.8	5.5
SE	156	53%	2.1	6.27	165	56%	2.3	7.3
SI	4	13%	1.6	0.14	16	45%	2.9	0.9
SK	23	24%	2.4	1.06	47	49%	3.4	3.1
UK	21	2%	1.0	0.41	503	37%	3.4	33.9
EU28	**1343**	**12%**	**2.0**	**51.5**[a]	**5398**	**50%**	**3.0**	**318**

[a] Note that a corrected sum of 48.5 billion euro is used since both DK (6.92−4.0 = 2.92 billion euro) and LT (1.54−1.5 = 0.04 billion euro) already at current conditions have expanded district heating beyond the stipulated saturation level.

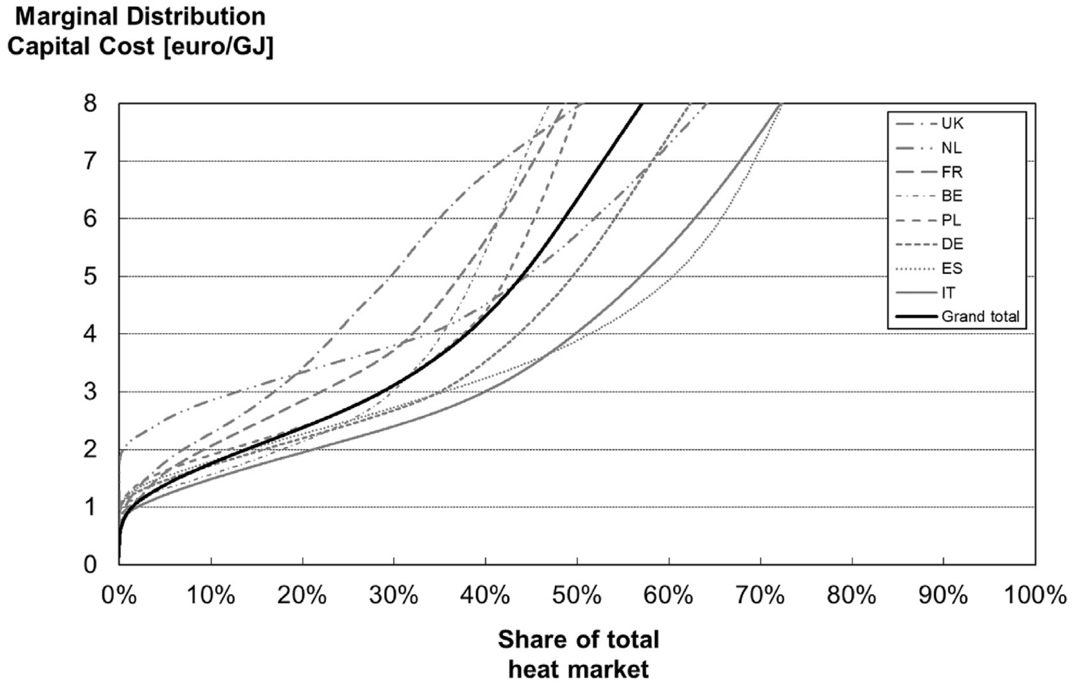

Fig. 10. Current marginal distribution capital cost levels and the corresponding district heat market shares for eight selected member states with largest expansion volumes, according to physical suitability by heat density classes 4 and 5 (EU28 average heat market share of ~50% at marginal distribution capital cost of 6.34 euro/GJ).

Table 4
Expansion of district heating on residential and service sector heat markets for eight selected EU28 member states with largest expansion volumes, according to physical suitability by heat density classes 4 and 5 (EU28 average heat market share of ~50% at marginal distribution capital cost of 6.34 euro/GJ).

MS	DH [PJ/a]	Expansion factor [−]	I [billion euro]
DE	1076	5	69.3
IT	777	16	45.9
FR	587	8	39.4
UK	482	24	33.5
ES	326	144	19.9
NL	209	11	16.5
BE	132	27	7.0
PL	98	1.5	8.4
Total	**3687**	**30**	**240**
EU28	**4076**	**4**	**269**

density classes. The two aggregated EU28 averages became an average annual heat demand per capita of 23.7 GJ per capita and an average population density of 5635 inhabitants per square kilometre. The effective EU28 average heat density became then 134 MJ/m^2. Located to the right in the figure, most cold countries with high heat demands per capita have low population densities; while warm countries with low heat demands per capita (located to the left in the figure) have high population densities. This characteristic circumstance results in a moderate variation of the national heat density averages among the member states.

The arithmetical average heat density among the EU28 member states became 139 MJ/m^2 with a small standard deviation of 37 MJ/m^2. Hence, most countries have average heat densities in dense areas between 100 and 175 MJ/m^2. Below this interval, the lowest heat densities appear in Cyprus (57 MJ/m^2), Croatia (92 MJ/m^2), and Portugal (92 MJ/m^2) giving high heat distribution costs. Above the average interval, the highest heat densities are found in Latvia (248 MJ/m^2), Sweden (190 MJ/m^2), and Finland (181 MJ/m^2) giving low heat distribution costs. Some paradoxes appear inside the average interval, since both Italy (171 MJ/m^2) and Spain (156 MJ/m^2) have higher heat densities (and lower heat distribution costs) than for example Denmark (142 MJ/m^2) and Germany (139 MJ/m^2). Although the heat demands per capita are higher in Denmark and Germany, the population densities are much higher in Italy and Spain.

The major implication from this short analysis of estimated national heat densities for dense areas is that the heat distribution costs are quite similar in the member states. This implication harmonises with the results presented in Fig. 6.

4. Discussion

In view of the presented suitability conditions for feasible network heat distribution, and especially so considering the influence of population density on the physical suitability metric, the since-long consistent trend of increasing urbanisation in Europe is worthy a brief consideration. While total EU28 population counts, which after decades of continuous growth appear to level out and begin to decline by the year 2045 [85], the growth of the urban population share exhibit no such indication of decline. On the contrary, compared to a 73% fraction in 2015, according to Ref. [86], four out of five Europeans will be urban dwellers in the year 2050, which would imply even more densely populated metropolitan areas in the decades to come.

This trend may partly counteract the simultaneous development towards lower specific heat demands in future buildings in Europe, which inevitably will lead to reduced total heat demands in the considered sectors. For 2050, relative to 2015 levels, this reduction was assessed in the Heat Roadmap Europe project for 14 member states representing 90% of these demands at minus ~20% (baseline) and minus ~24% (Heat Roadmap) respectively, according to the future scenarios developed in Ref. [87] and further presented in Ref. [88]. This implies that an actual future EU28 expansion volume at market saturation (~50%) would be found within the interval 4.1 EJ to 4.3 EJ per year rather than at the 5.4 EJ per year as

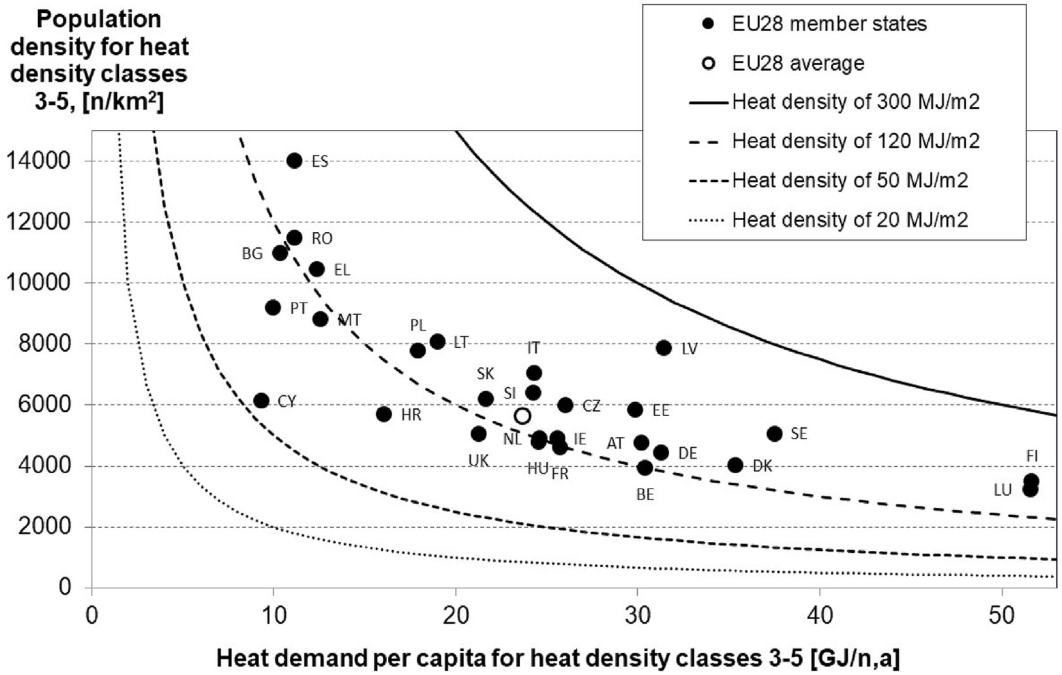

Fig. 11. Population density averages versus annual heat demands per capita for heat density classes 3–5 (including all land areas with heat densities above 50 MJ/m^2 per year) for the EU28 member states. The product of these two parameters equals the heat density according to Eq. (1) and the lines for the four threshold heat densities have also been included for facilitating the interpretation of the diagram.

stipulated here. However, since neither future heat demand volumes nor their spatial distribution can be known at present, this interval must be regarded as a general conjecture rather than as a dedicated prognosis for the future.

In this respect, it should also be underlined that the modelling of saturation rates and expansion volumes were performed under the general assumption of 100% connection rates, meaning that all building heat demands in a given hectare cell were modelled as being provided by district heat. In practise, although not analysed here, connection rates lower than the modelled level should be expected. However, very high connection rates, above 90%, are not uncommon in urban areas and cities operating large district heating systems today.

As for economic suitability, this study has analysed the demand and the distribution aspect of district heating only, while the third aspect influencing its overall feasibility, that of heat supply, has been excluded from these analyses since it represents another research field in its own right. However, this third aspect, as outlined by the primary energy cost and the ability to pay for recycled heat in Fig. 1, constitute a key cost component in the total cost for district heat and may therefore be regarded as an additional factor determining economic suitability. On this fact rests the fundamental insight that large-scale thermal synergies (such as excess heat recoveries from energy, industry, and commercial sector activities), are attainable only if cost-efficient network heat distribution infrastructures are in place. If not, available excess heat resources will either be practically impossible to recover or too expensive to distribute for utilisation. If indeed, the recovery and reuse of such available excess heat resources constitute the very fabric of the structural energy efficiency properties that district heating has to offer.

Here, the noteworthy distinction emphasised in the Heat Roadmap Europe project, between individual energy efficiency measures (demand side) and structural energy efficiency measures (supply side), facilitates a recognition of the two principal approaches whereby primary energy demands may be reduced, and of the appropriate balance to be sought between them. As the European community strives for a circular economy [89], an energy union [4], for higher integration of renewable energy sources [90], and for significant reductions of primary energy demands [91], the general project recommendation for the building heat market is consequently to aim for cost-optimal combinations of both individual and structural measures [15,84]. The future energy infrastructure landscape that this recommendation outlines is approaching that of so-called *Smart Energy Systems* [92–95], where e.g. high levels of integration between power, gas, and thermal networks, in combination with various energy storage solutions, provide the necessary availability and flexibility for its proper functionality [96–99].

The comparison of current and saturated deployment levels of district heating on the 28 national EU member state heat markets reveals clearly that very different progress has been made in different countries. Two member states, Denmark and Lithuania, has already today reached market penetration levels above those characterised here as saturated levels, and a few others, e.g. Sweden, Latvia, Finland, and Estonia, are very close at reaching such levels under current conditions. Given that physical as well as economic suitability for district heating similar to that present in these countries are present also in several other countries, e.g. Austria, Italy, Luxembourg, Germany, and Spain, the relatively low heat market shares found in these latter member states today, compared to full saturation levels, must be explained by other dimensions of causes. Although beyond the scope of this study to investigate more thoroughly, such dimensions could be those of national decisions and discourses, cultural and traditional preferences, as well as other particular circumstances unique for each respective country.

The introduction of suitability concepts for district heating may in this respect provide a new vocabulary by which to express more precise explanations as for the reasons and causes why district heating might be a dismissed or favoured heating solution on different national heat markets. While physical suitability for district heating very well may exist, this might be so under pure economic, or political, or other, conditions that reduces the economic suitability for its actual deployment. Hence, by elaborating such suitability concepts further and by introducing, for example, corresponding distinctions with regard to local availability of excess and renewable heat supply (resource suitability), governmental and jurisdictional devotion and preparedness (political suitability), public awareness and traditional technology preferences (cultural suitability) etc., a deeper and more profound understanding of nation-specific conditions may be obtained. Given the acceptance and establishment of such concepts, any discussion as to why a technology solution, such as district heating, might be deployed in disagreement with its physical suitability, should be in access of a more adequate terminology whereby to determine the causes for this state-of-affairs, which eventually could enable greater success in addressing them.

Finally, with regards to the simple aggregated answer as to why district heating can be viable concerning physical suitability, it is quite a paradox that some member states with none or very limited deployment of district heating today, in high density areas in fact are better suited for district heating than are many member states with high deployment levels. While many Southern member states have lower than EU28 average heat demands per capita in such high-density areas, they simultaneously display significantly higher population densities than do their Northern counterparts, which amounts to the fact that physical suitability for district heating, principally, is equally present in European high density areas irrespective of geographical location, as outlined in Fig. 11.

5. Conclusions

The main conclusion from this work is that the deployment of district heating in EU28, on average, is far from having reached a saturated state, on the contrary, its further expansion in e.g. inner city areas should be associated with generally beneficial feasibility conditions. The main explanation for this is the observable tendency of continued population clustering into towns, suburbs, and city areas, which leads to a corresponding spatial concentration of residential and service sector building heat demands. Hereby, there are no major principal market barriers for the proposed introduction of 4th generation district heating [100] with respect to heat distribution costs.

In response to the first research question, the physical suitability for district heating must be considered high since principally half of the total sector heat demand originate in urban areas characterised as dense and very dense. The significance of this cannot be other than to conclude on the generally high level of physical suitability for district heating in European urban areas, although, both local and national deviations from these general conditions are present. Conversely, it may accordingly be stated that, on average, other local heat generation alternatives, such as heat pumps, biomass boilers etc., may certainly represent appropriate choices on those heat markets segments that are characterised by more sparsely concentrated populations.

Second, concerning economic suitability, specific marginal investment costs for district heating expansions, up to half of the EU28 residential and service sector heat market, are expected to be found in the interval between zero and six euro per gigajoule (corresponding to specific average investment costs between zero and three euro per gigajoule). Here, naturally, significant variations are as well present among the 28 member states, where this cost interval is correspondingly broader in warmer climate areas, and narrower in colder regions. However, a key message from this work is that this metric always should be evaluated locally in each particular case, due to the influence of other external factors (e.g. investment strategies).

Third, with reference to the found general level of physical suitability, current deployment levels of district heating in the EU28 member states relate quite differently to the levels assessed here as economically suitable. Two member states (Denmark and Lithuania) have already expanded district heating beyond these levels, while for EU28 on average, a four-fold district heating expansion factor, from current levels, indicates the vast presence of economically feasible deployment opportunities for district heating in densely populated urban areas around Europe. The magnitude of an EU28 district heat market if saturated to its full extent, according to physical and economic suitability, has been found to represent principally half of the current total residential and service sector heat market. If fully saturated, this heat market share represents an expansion investment volume for future district heating networks of approximately 270 billion euro. By identifying the eight member states with the largest expansion volumes at current, the study has further pinpointed the most relevant national heat markets where such an expansion of district heating would have most impact. Together, these eight countries represent nine tenths of the total expansion volume, both in terms of annual heat deliveries and total investments.

Fourth, in view of the quite startling results presented in this paper, which principally confirms the findings of the original paper by arriving at a vast feasible expansion potential for district heating in Europe, it is recognised that additional concepts are needed if to fully understand and interpret current deployment levels. For, how should we explain the fact that district heating has remained such a marginal occurrence on the EU28 residential and service sector heat market in general, when both physical and economic suitability conditions for its expansion are so widely in place? Although this is not the context where to ponder on a more exhaustive answer to this question, the findings from this work suggests that many central European countries have focussed more on the specific heat demand metric of buildings when assessing opportunities for district heating, and less so on the heat density parameter itself. Because it is by the spatial concentration of heat demands, and not primarily by their volumetric magnitudes, that beneficial conditions for viable district heat distribution are formed.

Declaration of interest

None.

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Appendix

Table A.1
Land use areas by heat density classes for EU28 member states, in thousand square kilometres (left) and relative shares of total national land use areas (right). Heat density classes as defined in Table 1.

Land area by heat density class [kkm^2]								Land area by heat density class [%]					
MS	0	1	2	3	4	5	Total	0	1	2	3	4	5
AT	74.8	6.7	1.2	0.83	0.22	0.13	83.9	89%	8%	1.4%	1.0%	0.3%	0.16%
BE	23.8	3.2	1.5	1.69	0.31	0.16	30.7	78%	11%	4.8%	5.5%	1.0%	0.53%
BG	105.7	4.6	0.4	0.22	0.11	0.00	111.0	95%	4%	0.3%	0.2%	0.1%	0.00%
CY	8.0	1.1	0.1	0.02	0.00	0.00	9.2	86%	12%	1.5%	0.2%	0.0%	0.00%
CZ	70.3	6.2	1.2	0.60	0.39	0.13	78.9	89%	8%	1.6%	0.8%	0.5%	0.17%
DE	300.6	36.2	6.5	9.66	4.03	1.35	358.3	84%	10%	1.8%	2.7%	1.1%	0.38%
DK	35.0	6.5	0.8	0.57	0.20	0.08	43.2	81%	15%	1.8%	1.3%	0.5%	0.20%
EE	42.8	2.3	0.1	0.07	0.04	0.02	45.3	94%	5%	0.3%	0.2%	0.1%	0.05%
EL	124.8	5.9	0.7	0.33	0.18	0.03	131.9	95%	4%	0.5%	0.3%	0.1%	0.02%
ES	483.0	10.9	2.1	1.26	0.92	0.26	498.5	97%	2%	0.4%	0.3%	0.2%	0.05%
FI	329.2	6.5	0.9	0.62	0.18	0.12	337.5	98%	2%	0.3%	0.2%	0.1%	0.03%
FR	469.6	62.1	8.0	6.72	2.25	0.49	549.1	86%	11%	1.5%	1.2%	0.4%	0.09%
HR	50.9	4.7	0.6	0.28	0.07	0.00	56.5	90%	8%	1.1%	0.5%	0.1%	0.01%
HU	85.3	4.6	2.1	0.77	0.14	0.10	93.0	92%	5%	2.2%	0.8%	0.1%	0.11%
IE	60.1	9.4	0.6	0.42	0.01	0.04	70.6	85%	13%	0.9%	0.6%	0.0%	0.06%
IT	261.7	29.7	3.6	3.06	2.40	0.82	301.3	87%	10%	1.2%	1.0%	0.8%	0.27%
LT	60.0	5.1	0.2	0.09	0.08	0.01	65.4	92%	8%	0.3%	0.1%	0.1%	0.02%
LU	2.2	0.2	0.1	0.08	0.04	0.02	2.6	87%	6%	2.2%	3.0%	1.5%	0.69%
LV	61.8	3.5	0.1	0.06	0.05	0.04	65.5	94%	5%	0.1%	0.1%	0.1%	0.07%
MT	0.1	0.1	0.0	0.01	0.01	0.00	0.3	46%	43%	5.1%	3.6%	2.0%	0.04%
NL	26.9	7.1	0.7	1.95	1.18	0.05	37.8	71%	19%	1.8%	5.1%	3.1%	0.12%
PL	277.1	29.3	4.6	1.83	0.79	0.31	313.9	88%	9%	1.5%	0.6%	0.3%	0.10%
PT	79.6	8.6	0.3	0.26	0.06	0.00	88.8	90%	10%	0.4%	0.3%	0.1%	0.00%
RO	223.0	14.2	1.2	0.36	0.30	0.01	239.1	93%	6%	0.5%	0.2%	0.1%	0.00%
SE	436.3	11.1	1.3	0.68	0.27	0.21	449.9	97%	2%	0.3%	0.2%	0.1%	0.05%
SI	18.9	1.1	0.2	0.07	0.05	0.02	20.3	93%	5%	1.0%	0.4%	0.2%	0.08%
SK	45.3	2.5	0.7	0.27	0.17	0.03	49.0	92%	5%	1.4%	0.6%	0.3%	0.06%
UK	220.1	13.6	2.8	9.03	1.89	0.35	247.8	89%	5%	1.1%	3.6%	0.8%	0.14%
EU28	3966.9	297.0	42.6	41.80	16.34	4.81	4369.4	91%	7%	1.0%	1.0%	0.4%	0.11%

Table A.2
Population by heat density classes for EU28 member states, in million inhabitants (left) and relative shares of total national population counts (right). Heat density classes as defined in Table 1.

Population by heat density class [Mn]								Population by heat density class [%]					
MS	0[a]	1	2	3	4	5	Total	0	1	2	3	4	5
AT	0.19	1.08	1.74	2.91	1.15	1.52	8.58	2%	13%	20%	34%	13%	18%
BE	0.27	0.58	1.90	5.59	1.45	1.45	11.24	2%	5%	17%	50%	13%	13%
BG	−0.13	2.15	1.47	1.67	1.83	0.20	7.20	−2%	30%	20%	23%	25%	3%
CY	−0.26	0.45	0.55	0.10	0	0	0.85	−30%	54%	65%	12%	0%	0%
CZ	0.11	1.34	2.34	2.38	2.48	1.89	10.54	1%	13%	22%	23%	24%	18%
DE	1.02	4.38	9.11	33.12	20.44	13.12	81.20	1%	5%	11%	41%	25%	16%
DK	0.21	0.78	1.26	1.78	0.78	0.85	5.66	4%	14%	22%	31%	14%	15%
EE	0.03	0.27	0.21	0.26	0.28	0.26	1.31	2%	20%	16%	20%	21%	20%
EL	0.68	2.50	1.98	2.23	2.64	0.83	10.86	6%	23%	18%	21%	24%	8%
ES	2.00	3.21	7.00	9.44	13.82	10.97	46.45	4%	7%	15%	20%	30%	24%
FI	0.49	0.91	0.85	1.46	1.09	0.67	5.47	9%	17%	15%	27%	20%	12%
FR	3.82	7.79	11.30	21.85	12.25	9.45	66.46	6%	12%	17%	33%	18%	14%
HR	0.07	0.82	1.31	1.24	0.72	0.07	4.23	2%	19%	31%	29%	17%	2%
HU	−0.07	0.93	4.17	3.66	0.52	0.64	9.86	−1%	9%	42%	37%	5%	6%
IE	0.17	0.99	1.20	2.11	0.08	0.13	4.68	4%	21%	26%	45%	2%	3%
IT	1.93	6.82	7.83	13.30	17.97	12.95	60.80	3%	11%	13%	22%	30%	21%
LT	−0.09	1.00	0.55	0.51	0.69	0.26	2.92	−3%	34%	19%	17%	24%	9%
LU	0.05	0.02	0.05	0.19	0.19	0.07	0.56	9%	4%	9%	33%	33%	12%
LV	−0.08	0.66	0.22	0.26	0.40	0.53	1.99	−4%	33%	11%	13%	20%	27%
MT	0.04	0.10	0.15	0.10	0.05	0.00	0.44	8%	22%	34%	23%	12%	0%
NL	0.26	0.53	0.58	6.79	8.20	0.55	16.90	2%	3%	3%	40%	49%	3%
PL	−0.38	5.77	9.74	9.99	8.40	4.48	38.01	−1%	15%	26%	26%	22%	12%
PT	0.54	5.01	1.82	2.04	0.97	0.00	10.37	5%	48%	18%	20%	9%	0%
RO	−0.21	7.83	4.47	2.72	4.63	0.44	19.87	−1%	39%	22%	14%	23%	2%
SE	0.33	1.55	1.98	2.39	1.76	1.74	9.75	3%	16%	20%	24%	18%	18%
SI	0.13	0.61	0.45	0.31	0.29	0.27	2.06	6%	29%	22%	15%	14%	13%

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Table A.2 (*continued*)

Population by heat density class [Mn]								Population by heat density class [%]					
MS	0[a]	1	2	3	4	5	Total	0	1	2	3	4	5
SK	0.02	0.82	1.66	1.22	1.18	0.51	5.42	0%	15%	31%	23%	22%	9%
UK	2.31	1.54	4.09	45.47	10.10	1.37	64.88	4%	2%	6%	70%	16%	2%
EU28	13.46	60.43	79.95	175.10	114.39	65.22	508.54	3%	12%	16%	34%	22%	13%

[a] For the assessment of population counts belonging to this class, a comparison to total member state population counts [101], was made. In this comparison, when subtracting the sum of all population counts attributed to heat density classes 1–5, as found by use of [51], from those of [101], the remaining difference has been assigned to the zero class. Due partly to different reference years (and total volumes) in the two datasets, 2011 in Ref. [51] and 2015 in Ref. [101], and due partly to aggregation mechanisms in the zonal statistics operation (where e.g. the identification of grid cells located at national borders occasionally fails, resulting in exclusion), this has resulted in negative numbers in a few instances.

Table A.3

Physical suitability for district heating by aggregated member state hectare grid cell heat demands per heat density class, in volumes (left) and relative shares of total national residential and service sector heat markets (right). Heat density classes as defined in Table 1. The three last columns to the right consider aggregated annual heat demands per capita, population densities and average heat densities for heat density classes 3–5 and constitutes input to Fig. 11.

Heat demand by heat density class [PJ]							Heat demand by heat density class [%]					Aggregated by heat density classes 3–5		
MS	1	2	3	4	5	Total	1	2	3	4	5	GJ/capita	n/km^2	MJ/m^2
AT	25	39	59	41	69	232	11%	17%	25%	17%	30%	30.2	4758	144
BE	16	50	122	59	77	324	5%	15%	38%	18%	24%	30.4	3935	120
BG	18	12	17	19	2	68	27%	17%	25%	29%	2%	10.3	10,992	114
CY	3	4	1	0	0	8	41%	48%	11%	0%	0%	9.3	6149	57
CZ	22	39	45	74	56	237	9%	17%	19%	31%	24%	26.0	6007	156
DE	106	222	736	766	583	2413	4%	9%	31%	32%	24%	31.3	4432	139
DK	16	27	42	37	42	164	10%	16%	25%	22%	26%	35.3	4018	142
EE	5	4	5	8	11	34	16%	13%	16%	24%	31%	29.8	5844	174
EL	25	21	26	34	10	116	22%	18%	22%	29%	9%	12.4	10,458	129
ES	37	71	98	172	111	489	8%	14%	20%	35%	23%	11.1	14,024	156
FI	31	29	48	33	86	226	14%	13%	21%	15%	38%	51.6	3505	181
FR	179	263	496	403	221	1562	11%	17%	32%	26%	14%	25.7	4604	118
HR	14	21	20	12	1	68	20%	31%	29%	17%	1%	16.1	5714	92
HU	20	71	48	29	41	210	10%	34%	23%	14%	19%	24.6	4790	118
IE	24	21	27	2	30	104	23%	20%	26%	2%	28%	25.6	4918	126
IT	94	114	249	445	381	1283	7%	9%	19%	35%	30%	24.3	7054	171
LT	12	6	7	15	6	46	25%	14%	15%	34%	12%	19.0	8085	153
LU	1	2	7	7	10	26	4%	7%	26%	26%	37%	51.5	3239	167
LV	6	2	5	9	23	46	14%	5%	11%	21%	50%	31.4	7880	248
MT	0	0	1	1	0	3	16%	16%	33%	34%	2%	12.6	8822	111
NL	20	23	169	198	16	426	5%	5%	40%	47%	4%	24.6	4902	121
PL	97	152	126	153	130	658	15%	23%	19%	23%	20%	17.9	7779	139
PT	23	10	20	10	0	64	36%	17%	32%	15%	0%	10.0	9207	92
RO	63	34	28	54	4	183	34%	18%	16%	30%	2%	11.1	11,489	128
SE	32	41	50	51	120	294	11%	14%	17%	17%	41%	37.5	5069	190
SI	8	6	6	9	7	35	22%	17%	16%	25%	20%	24.3	6412	156
SK	11	22	21	31	11	96	11%	23%	22%	33%	12%	21.7	6196	134
UK	58	94	725	331	154	1363	4%	7%	53%	24%	11%	21.3	5053	107
EU28	968	1399	3205	3002	2201	10,776	9%	13%	30%	28%	20%	23.7	5635	134

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