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District heating potential in the EU-27: Evaluating the impacts of heat demand reduction and market share growth

Mostafa Fallahnejad [a,*], Lukas Kranzl [a], Reinhard Haas [a], Marcus Hummel [b], Andreas Müller [b], Luis Sánchez García [c], Urban Persson [c]

[a] TU Wien, Institute of Energy Systems and Electrical Drives – Energy Economics Group, Gusshausstrasse 25-29/370-3, 1040 Wien, Austria
[b] e-think Energy Research, Argentinierstrasse 18/10, 1040 Wien, Austria
[c] School of Business, Innovation and Sustainability, Halmstad University, 301 18 Halmstad, Sweden

HIGHLIGHTS

- A novel method for analyzing district heating potential in the EU-27 is presented.
- District heating can cover 31% of heat demand (non-industry) in EU-27 up to 2050.
- Grid expansion is needed in economically favorable areas to reduce specific costs.
- A yearly investment of €11.7B at the EU level is required for the grid expansion.

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ABSTRACT

This paper presents a novel approach to modeling the gradual reduction in heat demand and the evolving expansion of district heating (DH) grids for assessing the DH potential in EU member states (MS). It introduces new methodological elements for modeling the impact of connection rates below 100% on heat distribution costs in both dense and sparse areas. The projected heat demand in 2050 is derived from a decarbonization scenario published by the EU, which would lead to a reduction in demand from 3128 TWh in 2020 to 1709 TWh by 2050. The proposed approach yields information on economic DH areas, DH potential, and average heat distribution costs. The results confirm the need to expand DH grids to maintain supply levels in view of decreasing heat demand. The proportion of DH potential from the total demand in the EU-27 rises from 15% in 2020 to 31% in 2050. The analysis of DH areas shows that 39% of the DH potential is in areas with heat distribution costs above 35 EUR/MWh, but most MS have average heat distribution costs between 28 and 32 EUR/MWh. The study reveals that over 40% of the EU's heat demand is in regions with high potential for implementing DH.

1. Introduction

The European Union (EU) has set ambitious climate targets to become climate neutral by 2050. Decarbonizing the heating sector is one of the key challenges if this target is to be achieved. District heating (DH) is a technology with both the economic and environmental potential to contribute to the decarbonization of the heating sector in Europe [1] and has therefore been studied from different perspectives.

Sven Werner provides an overview of the district heating and cooling (DHC) in the world [2]. He identifies the disconnection of customers from DH in Eastern Europe and simultaneous DH expansions in other European countries as the main reason for the stagnation of DH supply in Europe at 2.5 EJ/year from 1990 to 2014, referring to the potential of DH systems as a viable heat supply option in the future. Werner emphasizes, however, the need for additional effort in identifying, assessing, and implementing DH potential.

The Heat Roadmap Europe (HRE) [3] can be considered one of the front-runners for identifying and assessing DH potential in Europe. The project is focussed on developing low-carbon heating and cooling strategies. HRE foresees an upward potential for DH supply from its current 10% share to 50% by 2050 [4].

Estimating the DH potential through geographic information systems

* Corresponding author.
E-mail address: fallahnejad@eeg.tuwien.ac.at (M. Fallahnejad).

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(GIS) and heat mapping has been practised on different geographical levels. Novosel et al. applied heat mapping to the case study of Zagreb [5]. They calculate the DH potential at different cost levels. Patureau et al. used GIS to categorize regions in France based on their suitability for the low-temperature DH systems and report France's potential for low-temperature DHC. In a GIS-based approach, Leurent calculates the linear heat density and DH potential using a heat density map of France [6].

The estimation of the DH potential based on heat distribution costs has been addressed in several papers. Möller et al. present the share of annual final heat demand that can be covered under different average annualized investment costs of DH for 14 European countries [7]. Fallahnejad et al. analyse the impact of transmission and distribution grid costs on DH potential for the case study of Vienna [8]. They conclude that policy interventions for implementing DH priority areas are required to achieve the full potential of the DH in Vienna. Dénarié et al. propose a method to assess the grid length and heat distribution costs of potential DH systems in Italy [9].

The potential of RES-based DH systems has also been the focus of research work. GIS is often used as a means for calculating the potential. Soltero et al. studied the potential of biomass DH systems in 499 rural areas in Spain [10]. They identify 188 potential areas for implementing the biomass-based DH system, of which 185 rural areas are economically viable.

Matching of source and sinks is another approach for estimating DH potential. Nielsen and Möller performed a GIS-based analysis of future DH potential in Denmark [11]. They demonstrate the potential for DH expansion in many areas of Denmark. High production costs and heat losses are enumerated as barriers to expanding the DH in other regions. Persson et al. analyse the excess heat volumes from fuel combustion activities in the power and industry sectors and identify synergy regions for utilizing the excess heat on the EU-27 level. Pampuri et al. developed a heat demand density map for the Ticino Canton in Switzerland and set a demand threshold to identify suitable areas for DH. Subsequently, the availability of renewable sources for heat supply in the areas identified was investigated. Fallahnejad et al. studied the economic potential of DH under climate neutrality for the case of Austria [12] and in line with Article 14 and Annex VIII of the revised Energy Efficiency Directive [13]. Having identified potential DH areas and nearby RES, they calculate the economic potential of DH by dispatch of available renewable energy sources, and compare the DH costs with decentral supply options.

There are studies in the literature that estimate the potential of DH considering future heat demand and supply systems. Connolly et al. analyse a strategy focusing on the expansion of DH along with the utilization of waste heat, consideration of heat savings and integration of renewable energy sources [14]. They conclude that a heat supply strategy based on DH systems could lead to cost reduction. Champers et al. mapped the DH potential under evolving heat demand scenarios and technologies for the case of Switzerland [15]. They conclude that the DH potential from high-temperature grids would decrease considerably while the DH potential from low-temperature grids would significantly increase.

There is a range of studies that deal with detailed DH grid modeling for the calculation of the economic DH potential. These studies often use optimization or computational-intensive models and focus on a small area. Marquant et al. propose a clustering approach to analyse DH grid potential, considering both heat supply and demand [16]. Their simplified grid model uses a minimum-spanning-tree algorithm without distinguishing pipe dimensions, while the supply dispatch is calculated in higher detail. Stennikov et al. study the effective heat supply radius for DH systems, focusing on economic efficiency, hydraulic aspects, and supply security [17]. They applied their model to an existing DH grid, identifying effective heat supply radius and weak connections. Röder et al. developed DHNx, an open-source Python library, to analyse the impact of distributed storage systems in DH grid design and their economic benefits related to the piping system [18]. Lumbreras et al. assessed the economic feasibility of DH grids in urban areas, particularly for integrating industrial waste heat sources [19]. They emphasized the importance of data availability for replicability. Jebamalai et al. compared the grid costs of third and fifth-generation DH systems in Kortrijk, Belgium [20]. They concluded that a free low-temperature waste-heat source is essential for the economic implementation of the fifth-generation DH system. Wack et al. developed a non-linear topology optimization model for DH grids [21]. However, applying the model on a larger scale requires the relaxation of the model. Due to the intensity of the calculation and the high granularity of the required data, these approaches are not suitable for large geographical areas like the EU or national level.

Five gaps were identified in the literature, which will be addressed in this paper:

- All studies mentioned above provide great insights into the DH potential in their focus areas. However, many of the studies have not considered future demand developments. Furthermore, the new European climate targets and laws, such as the European Green Deal or Fit-for-55 package, have not been considered in the heat demand scenarios of these studies.
- The studies on the DH potential often consider 100% connection rates in DH areas for their economic analyses. However, implementing the DH grids is realized gradually due to various limitations, such as financial or human resource limitations. The gradual construction and implementation of DH grids affect the economics of DH systems. This gradual implementation has not been addressed in previous studies on the EU level.
- Many of the studies use the concept of the effective width (the relationship between a given land area and the DH trench length within this area) as proposed in [22] or [23] to calculate heat distribution costs. At the same time, the Horizon 2020 project sEEnergies [24] has recently published an updated, validated approach, introducing service pipes in addition to distribution pipes and adapting cost components for each EU member state [25]. The updated approach improves the estimation of the heat distribution costs.
- DH potential and its economic viability in sparse areas have been addressed in Swedish case studies by looking into the sparse district-heating research program of Swedish DH Association [26] or by analyzing the profitability of the sparse DH systems [27]. However, due to limited DH potential in sparse areas, these regions have not been the mainstream focus of research studies on the EU level. In this paper, sparse regions and their DH potential will be addressed as well.
- The whole approach is implemented in Python with an open-source license to facilitate the replicability of the results and the possibility of conducting further analyses under various heat demand scenarios. Furthermore, the outputs of the analyses follow the FAIR principle [28].

Accordingly, the main objectives of this paper are: (1) to study the impact of ambitious heat demand reductions on DH potential and consider the dynamic aspect of heat demand development in the calculation of heat distribution costs; (2) to consider the evolving DH market shares over time for the economic assessment of the DH grid; (3) to add methodological elements and steps for more accurate modeling of the sparse area and network lengths at DH market shares of below 100%. (4) to synthesize the heat distribution costs and DH potential and the economic implications for future DH expansions.

These objectives are followed in the proposed approach and the presentation of the results. The structure of the paper is as follows: Section 2 explains the data and scenarios used for the calculations. Section 3 explains the required step for the implementation of the approach and introduces a new modeling framework. Section 4 presents the results in detail. The results are further discussed in Section 5, and the approach's limitations are enumerated. Section 6 presents our conclusions.

2. Data preparation

The useful heat demand and gross floor area densities of the residential and service sectors for the years 2020 and 2050 in the form of GIS layers are the basis for the calculations in this paper. These layers were obtained from a report on "renewable space heating under the revised Renewable Energy Directive" published by the European Commission [29]. In this report, the Eurostat energy balances were used as the main source for the final energy demand on a national level in 2020. The future development of the gross floor area is defined exogenously. The demolition of buildings is based on the Weibull distribution and the average lifetime of the buildings. For the year 2050, an optimization model was used to obtain the final energy demands on a country level. The useful energy demands of each country are calculated accordingly. Finally, both useful energy demands and heated gross floor areas are first broken down to the NUTS 3 levels and subsequently to the hectare level using a number of regional indicators based on the method developed by Müller et al. [30]. The step for breaking demand to NUTS 3 helps to improve the calculation accuracy since certain statistical data, such as building census data, are available at this territorial unit. The breakdown from NUTS 3 to the hectare level assumes that the energy need in a plot area correlates with population, economic activity and climatic conditions in that area, as well as building properties, like the average construction period and volume-to-surface ratios of the buildings.

The EC report introduces five scenarios besides the baseline scenario, focusing on direct RES heating, electrification, e-fuels, hydrogen and DH [29]. The scenarios were compared quantitatively and qualitatively. Subsequently, a best-case scenario was developed by combining the feasible ways of decarbonising the building stock in the EU-27 countries. The heat demand and gross floor area densities presented in this paper are based mainly on the best-case scenario.

Fig. 1 shows the useful heat demand levels in 2020 and 2050 in the EU member states and the changes in this period according to the Best-Case scenario. Based on the best-case scenario, the useful heat demand of the residential and service sectors in EU-27 countries dramatically decreases from 3128.8 TWh in 2020 to 1709.1 TWh in 2050. The dramatic demand reductions can affect the DH potential. To understand the impact of the demand reductions on DH potential, a further heat demand density layer with a less intense demand reduction for 2050 is used. For this purpose, the baseline scenario (BL2050) from the sEEnergies project is employed [31] (Corresponding data of BL2050 scenario is available in [32]). The BL2050 scenario is an adapted version of the PRIMES scenario for 2050 [33,34]. Based on this scenario, the heat demand in EU-27 countries should reduce to 2088.7 TWh, 379.6 TWh higher than the best-case scenario.

DH market shares within DH areas are inputs for identifying the DH areas. Considering the decreasing heat demand levels, DH should be expanded further in many regions to maintain the supply level. Therefore, it is expected that DH systems should either maintain high market shares in DH areas or expand significantly till 2050. The impact of the DH market shares on the DH potential is studied in this regard. The values of DH market shares within DH areas in 2020 and 2050, presented in Fig. 2, are set so that:

- The obtained DH potentials in 2020 comply with energy balances,
- Considering 2020's DH market shares within DH areas and with regard to the network construction costs in each country, a high DH market share of between 70% and 90% within DH areas is achieved or maintained in 2050.

The DH shares within DH areas in 2050 are educated anticipations in alignment with current levels from mature DH markets (e.g., 2020's shares in Denmark and Sweden as shown in Fig. 2) and reflect levels which facilitate cost-effective heat distribution.

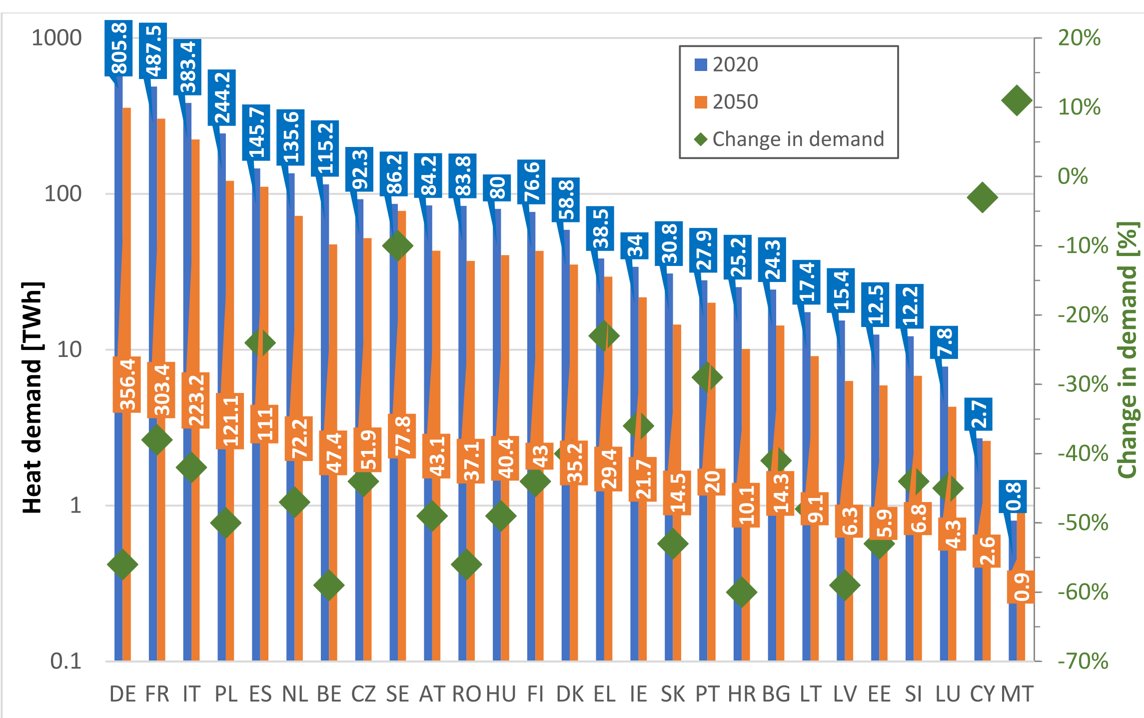

Fig. 1. Useful heat demand levels (TWh) in 2020 and 2050, and the relative changes in residential and tertiary sectors (secondary Y-axis) based on the best-case scenario.

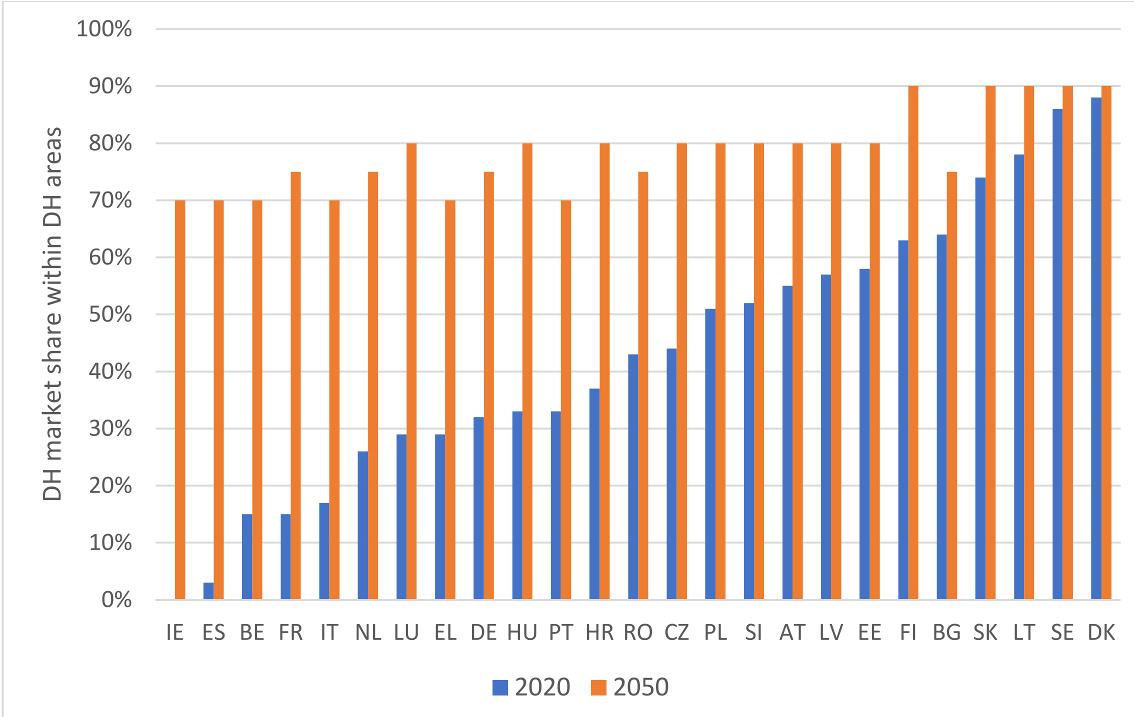

Fig. 2. DH market shares within DH areas used as inputs for the base year (2020) and target year (2050).

3. Method

This section explains the required steps for calculating the DH distribution and service pipe costs and the required investment for the grids based on the achieved DH market share within identified DH areas. In the context of this paper, the terms DH area, market share and potential are defined as follows:

- **DH area**: An area within a region where a DH system partially or fully supplies heat to the buildings. In this paper, a DH area can be as small as 1 ha (resolution of input data). Larger DH areas are composed of several coherent and connected hectare elements. For example, a city can have no, one, two or more DH areas.
- **DH market share within a district area (%)**: The share of heat demand in a DH area supplied by the DH system from total heat demand in the same area. In this paper, we use "DH market share" or "DH market share in DH areas" interchangeably. DH market shares are defined for each country separately and are model inputs.
- **DH potential (in MWh or GWh, or TWh)**: Shows the amount of energy supplied by the DH system. Considering the provided definition for the DH market share, the multiplication of DH market share in a country and its total heat demand does not provide the DH potential.

Given the above definitions, although the DH market shares are inputs to the model, DH potential cannot be calculated in advance. The calculation of the DH potential is possible once the extent and location of DH areas are identified. Section 3.3 elaborates the approach for the identification of the DH areas.

3.1. Heat distribution costs under 100% of market share in DH areas

In this section, we introduce a model for assessing the capital cost of DH grids in a national context and identifying the potential DH areas accordingly.

Persson et al. introduced a methodology to estimate the DH heat distribution costs [22,23]. Their methodology uses several independent input data, such as pipe diameter, construction costs, interest rate, and demographic data. Fig. 3 shows the schematic overview of the procedure to calculate DH distribution grid capital costs.

Uniform data on heat demand and gross floor area densities, introduced in the previous section, are used to apply this method uniformly to a large area. From the gross floor area densities, the plot ratio can be acquired. The following formulas can be applied to each hectare element of the heat demand and gross floor area density maps.

One key concept when assessing DH grid investment cost is the linear heat density, defined as the ratio of delivered heat by the DH system (Q_T) in a year to the total DH trench length (L), as shown in Eq. (1).

$$LinearHeatDensity = Q_T/L \; [GJ/(m.a)] \tag{1}$$

Persson and Werner use demographic data to calculate the linear heat density analytically. The calculation procedure is shown in Eqs. (2) to (4). They introduced the concept of effective width (w), which describes the relationship between a given land area (or plot ratio, pr) and the DH trench length within this area [35]. The approach has been used widely and the formulation updated a few times with the grid data of different cities. The sEEnergies project addresses one of the most recent updates [24] and provides formulations for the distribution and service pipes. The proposed update is the basis for the calculations performed in this paper. The effective width of the DH distribution grid can be obtained using Eq. (5). As Eq. (5) shows, the effective width is assumed to be constant in areas with plot ratios above 0.1353 (hereon, "high plot ratio areas").

$$q = Q_T/GFA \; \left[GJ/\left(m^2{\cdot}a\right)\right] \tag{2}$$

$$q_T = Q_T/A_L \; \left[GJ/\left(m^2{\cdot}a\right)\right] \tag{3}$$

$$LinearHeatDensity = \frac{Q_T}{L} = pr{\cdot}q{\cdot}w = q_T{\cdot}w \; [GJ/(m.a)] \tag{4}$$

$$w_{DistributionPipe} = A_L/L = \begin{cases} e^2/pr \; [m] \; 0 < pr \le 0.1353 \\ e^4 \; [m] \; pr > 0.1353 \end{cases} \tag{5}$$

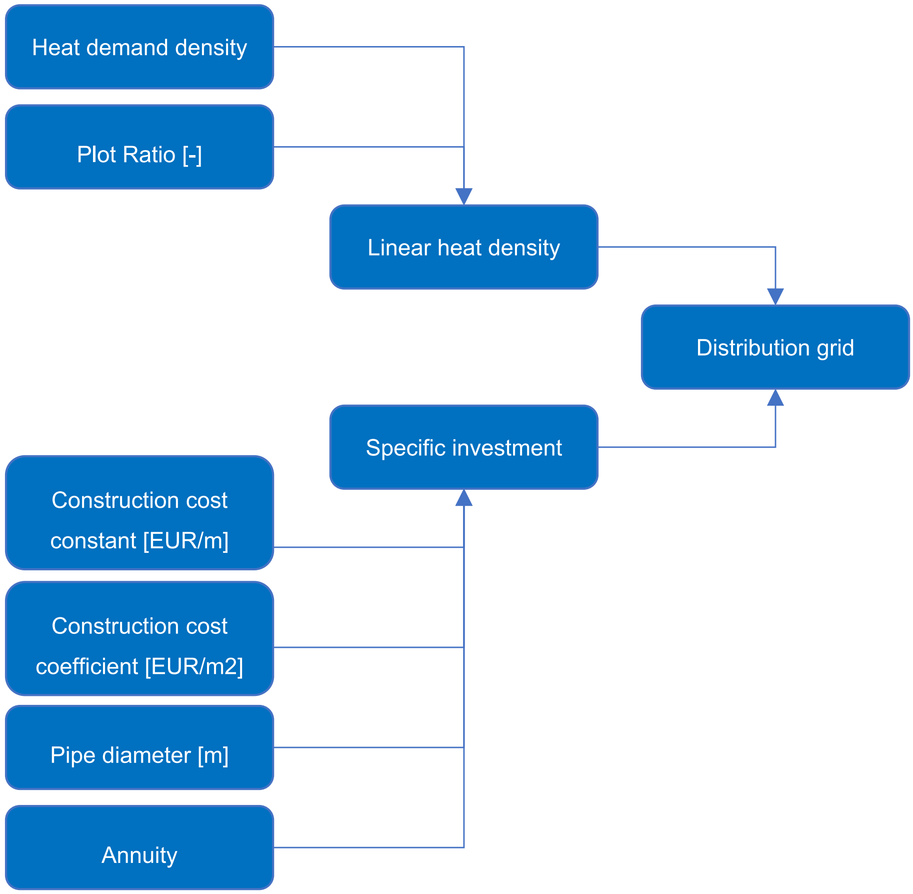

Fig. 3. Schematic overview of the procedure to calculate DH distribution grid capital costs.

The average distribution pipe diameter ($d_{a,DistributionPipe}$) in meters is calculated using the linear heat density and effective width. In areas with an annual heat demand below 1.5 GJ, the average distribution pipe diameter is set to 20 mm.

$$d_{a,DistributionPipe} = \begin{cases} 0.02, Q_T < 1.5\ GJ \\ 0.0486 \cdot ln(Q_T/L) + 0.0007, Q_T \geq 1.5\ GJ \end{cases} [m] \tag{6}$$

Service pipes are referred to as pipes that connect the buildings to the distribution pipes. The effective width of the service pipes ($d_{a,ServicePipe}$) is calculated using Eq. (7). An average diameter of 30 mm is considered for all service pipes. Only in areas with an annual heat demand below 1.5 GJ, the average service pipe diameter is set to 20 mm.

$$w_{ServicePipe} = A_L/L = \begin{cases} e^2/pr\ [m]\ 0 < pr \leq 0.1353 \\ e^{\frac{ln(pr)+3.5}{0.7737+0.18559 \bullet ln(pr)}}\ [m]\ pr > 0.1353 \end{cases} \tag{7}$$

$$d_{a,ServicePipe} = \begin{cases} 0.02, & Q_T < 1.5\ GJ \\ 0.03, & Q_T \geq 1.5\ GJ \end{cases} [m] \tag{8}$$

The specific grid investment cost (I/L) of both distribution and service pipes can be derived using Eq. (9). The slope and the intercept of the linear formula are referred to as construction cost constant (C_1) in EUR/m and construction cost coefficient (C_2) in EUR/m^2, respectively. The parameters C_1 and C_2 are obtained empirically based on the existing grids. Persson et al. calculate these factors for each EU member state [25]. These values are provided in the Appendix of this paper in Table A.1.

$$\frac{I}{L} = C_1 + C_2 \cdot d_a \left[\frac{€}{m}\right] \tag{9}$$

The specific cost of heat distribution ($Cost_{HeatDistribution,T}$) for each unit of delivered heat in year T can be obtained from Eq. (10). The annuity factor is obtained based on the interest rate (r) and the depreciation time (n) in years.

$$Cost_{HeatDistribution,T} = \frac{a.I}{Q_s} = \frac{a.\left(\frac{I}{L}\right)}{\left(\frac{Q_s}{L}\right)} = \frac{a}{q_{s,T}} \bullet \left(\frac{C_1 + C_2 \bullet d_{a,DistributionPipe}}{w_{DistributionPipe}} + \frac{C_1 + C_2 \bullet d_{a,ServicePipe}}{w_{ServicePipe}}\right) \left[\frac{€}{GJ}\right] \tag{10}$$

$$a = \frac{r \cdot (1+r)^n}{(1+r)^n - 1} \tag{11}$$

3.2. Heat distribution costs under evolving DH market share and heat demand

The expansion of DH and connecting new customers is a gradual process. Over time, retrofitting the building stock lowers heat consumption. The economic viability of the DH is affected by both DH heat supply over time and grid expansion. In this section, the equations provided in the previous section are adapted to reflect the impact of the evolving DH market share and heat demand.

The DH market share in a potential DH area shows the portion of heat demand that DH supplies in that area. Considering a time horizon of m years, the annual heat demand changes from its initial value (D_0) to its final value (D_m). It is assumed that the annual heat demands between the base year and target year follow the interpolation in Eq. (12). This equation leads to slightly higher heat demand reductions at the beginning of the study horizon and lower reductions near the end.

$$D_t = D_0 \bullet \sqrt[m]{(1 - D_m/D_0)^t} \tag{12}$$

$$t \in T = \{0, 1, 2, \ldots, m\} \tag{13}$$

The DH market share in the base year (MS_0) increases gradually to reach its value in the target year (MS_m). Accordingly, for each hectare element of the map, it is assumed that the delivered heat by DH in t^{th} year (Q_t) follows Eq. (14).

$$Q_t = D_t \bullet \left[MS_0 + t \bullet \frac{MS_m - MS_0}{m} \right] \tag{14}$$

The formulation of the effective width in Eqs. (5) and (7) should be adapted to include the impact of DH market shares of below 100% in DH areas. The effective width has an inverse relation with trench length and is a function of the plot ratio. For high plot ratios ($pr > 0.1353$), the effective width of distribution pipes is independent of the plot ratio. We therefore focus on the effective width in low plot ratio areas to find its relation with the DH market share in DH areas.

Chambers et al. show that DH pipeline length is mostly affected by the number of buildings in an area [15]. They provided an empirical formula for calculating the length of supply and return pipes. The trench length can be derived accordingly, as shown in Eq. (15).

$$L = l/2 = 65.3 \bullet ln(N_{buildings}) - 42.25 \tag{15}$$

Since the impact of the market share on effective width is only valid in sparse areas with a low plot ratio, we assume that a building is either fully supplied by DH or is not connected to the DH at all. In other words, we do not consider a partial supply of a building with a DH system. Therefore, we reformulate Eq. (15) and include the DH market share in its definition. In addition, an adjustment factor is added to the original formula of the effective width (Eq. (5)) for low plot ratio areas to reflect the impact of the DH market share, as shown in Eq. (17).

$$L = 65.3 \bullet ln(MS \bullet N_{buildings}) - 42.25 \tag{16}$$

$$L = A_L \bullet pr \bullet AdjFactor/e^2 \tag{17}$$

$$AdjFactor = f(MS) \tag{18}$$

$$0 < AdjFactor \leq 1 \tag{19}$$

The adjustment factor is defined as a function of the DH market share in DH areas. It can be derived by considering a market share of α%, as shown in Eq. (20).

$$\frac{L_{\alpha\%}}{L_{100\%}} = \frac{AdjFactor \bullet pr}{pr} = AdjFactor \tag{20}$$

From Eq. (5), a plot ratio of 0.1353 leads to a trench length of ca. 183.1 m in each hectare, equivalent to connecting 31 buildings based on Eq. (15).

Fig. 4 shows the adjustment factors as a function of the DH market share for different numbers of buildings in a hectare.

The number of buildings within each hectare of EU-27 countries

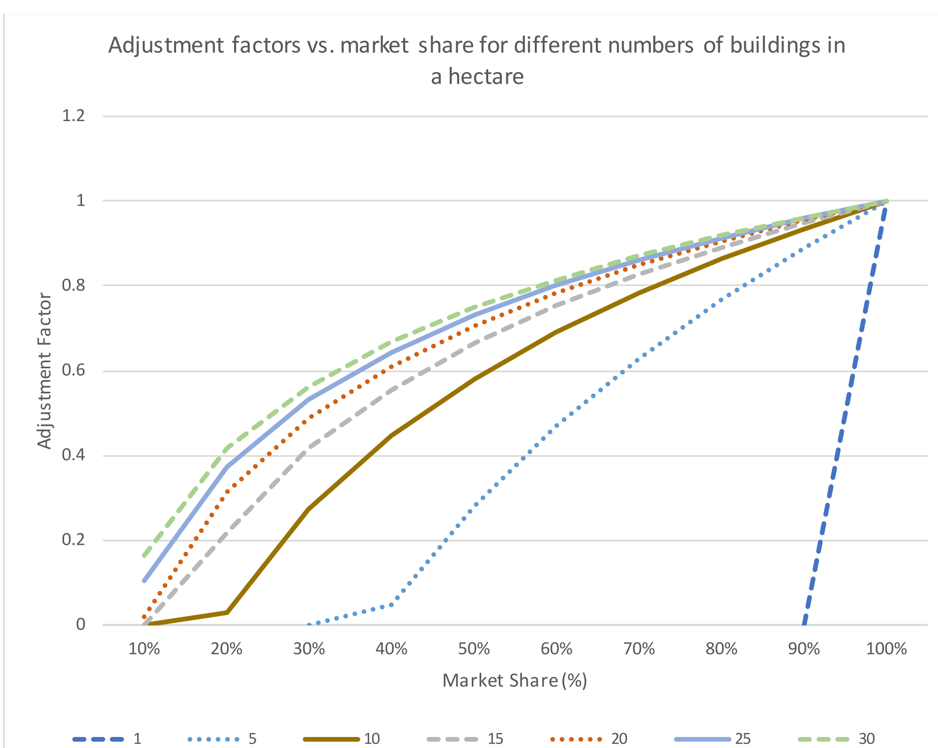

Fig. 4. Adjustment factors as a function of DH market shares for different numbers of buildings in a hectare.

cannot be obtained easily. However, there are normally few buildings within a hectare in sparse areas with low plot ratios. To simplify the calculation for the adjustment factor, the adjustment factor for ten buildings is used for all areas with a low plot ratio. We consider a minimum adjustment factor of 0.0279 for market shares below 20%. The fitted logarithmic trendline is provided in Eq. (21).

$$AdjFactor = \begin{cases} 0.0279, & MS < 20\% \\ 0.604 \cdot ln(MS) - 1.7815, & MS \geq 20\% \end{cases} \tag{21}$$

The adjustment factor is used to reformulate the effective width for both distribution and service pipes. In the original formulation of the effective width for the service pipes, under higher plot ratios, the effective width rises as the plot ratio rises. This behavior implies that connecting additional buildings in an area requires longer service pipes. Therefore, lower DH market shares should lead to lower effective width. However, a lower limit of 0.1353 is maintained for the multiplication of the plot ratio and adjustment factor, leading to an effective width of 41.53 m. The effective width formulations of distribution and service pipes are provided in Eq. (22) and Eq. (23), respectively.

$$w_{DistributionPipe} = A_L/L = \begin{cases} e^2/(AdjFactor \bullet pr)\ [m]\ 0 < pr \leq 0.1353 \\ e^4\ [m]\ pr > 0.1353 \end{cases} \tag{22}$$

Table 1
Input parameters for the study of the impact of the adjustment factor.

Parameter	Value	Unit
Heat density in the DH area	100 (for 4.1.1) & 500 (for 4.1.2)	MWh/ha
Construction cost constant (C1)	212	EUR/m
Construction cost coefficient (C2)	4464	EUR/m^2
Depreciation time	40	Year(s)
Interest rate	2	%

The method explained in this section has been fully implemented in Python and published with an open-source license [37].

4. Results

The results section is composed of three sub-sections, in which the impact of the adjustment factor is discussed first. Following this, the obtained DH potential and relevant indicators for the DH are presented.

4.1. The impact of the adjustment factor

This section looks into the impact of the adjustment factor and corresponding assumptions on the effective width, linear heat density, average pipe diameter, and heat distribution costs for different plot ratios. The parameters used for the calculation are listed in Table 1. Heat

$$w_{ServicePipe} = A_L/L = \begin{cases} e^2/(AdjFactor \bullet pr)\ [m]\ 0 < pr \leq 0.1353 \\ e^{\frac{ln(AdjFactor \bullet pr)+3.5}{0.7737+0.18559 \bullet ln(AdjFactor \bullet pr)}}\ [m]\ (pr > 0.1353) \wedge (pr \bullet AdjFactor > 0.1353) \\ 41.53\ [m]\ else \end{cases} \tag{23}$$

density levels of 100 and 500 MWh/ha for a low plot ratio case ($pr < 0.1353$), and a high plot ratio case are considered, respectively. A market share of 40% would mean that 40 MWh and 200 MWh of heat demands are covered by DH for each case, respectively.

Considering the annual evolution of both heat demand and DH market share, the specific cost of heat distribution ($Cost_{HeatDistribution}$) is obtained by Eq. (24). It is assumed that after the target year (m), the heat demand and supplied heat by DH remain constant.

$$Cost_{HeatDistribution} = \frac{1}{\sum_{t=0}^{m} q_{T,t} \bullet (1+r)^{-t} + \sum_{t=m}^{n} q_{T,m} \bullet (1+r)^{-t}} \bullet \left(\frac{C_1 + C_2 \bullet d_{a,DistributionPipe}}{w_{DistributionPipe}} + \frac{C_1 + C_2 \bullet d_{a,ServicePipe}}{w_{ServicePipe}} \right) \left[\frac{€}{GJ} \right] \tag{24}$$

The impact of the adjustment factor will be presented in Section 4.1.

3.3. Identification of DH areas

For the identification of potential DH areas, the proposed approach by Fallahnejad et al. is used [36]. Two conditions should be fulfilled to identify an area as a potential DH area. For each country, a heat distribution cost ceiling is set exogenously. The first condition ensures that the average distribution grid costs of any potential DH area in a country may not exceed the pre-defined cost ceiling for that country. This criterion limits heat distribution costs and is necessary since this study does not consider heat generation costs. The second condition sets a minimum annual DH demand of 5 GWh to be reached through the study horizon in order to identify an area as a potential DH area. DH areas are not identified based on administrative borders; therefore, more than one DH area might be identified within a town or city.

Both the above conditions, directly and indirectly, are related to the heat demand. The best-case scenario from [29] includes a dramatic heat demand reduction. Therefore, the approach is also applied to the baseline scenario obtained from [32]. Finally, the DH potentials obtained from each scenario are compared.

4.1.1. Distribution pipes and low plot ratio area

In low plot ratio areas, distribution pipes have a higher impact on the DH grid costs than the service pipes. In this section, the impact of the plot ratio and DH market share on effective width, average pipe diameter, linear heat density, and heat distribution cost is presented. The behavior of the effective width can be extended to the service pipes. However, considering the constant average pipe diameter for the service pipes, the other three parameters have slightly different behavior.

Fig. 5 shows the effective width as a function of the plot ratio for different DH market shares in a DH area. The following aspects can be identified in the figure:

- Generally, with the increase of the plot ratio, effective width decreases;
- A decrease in DH market share in the DH areas leads to an increase in the effective width.
- The impact of the DH market share in the DH areas declines as the plot ratio increases.

Linear heat density and the average pipe diameter have similar behavior, as shown in Fig. 6. It can be observed that:

- The linear heat density decreases as the plot ratio increases.
- Depending on the gradient (∇) of heat demand coverage at different DH market shares and the gradient of the trench length (or effective width), with the decrease of the DH market share, the average pipe

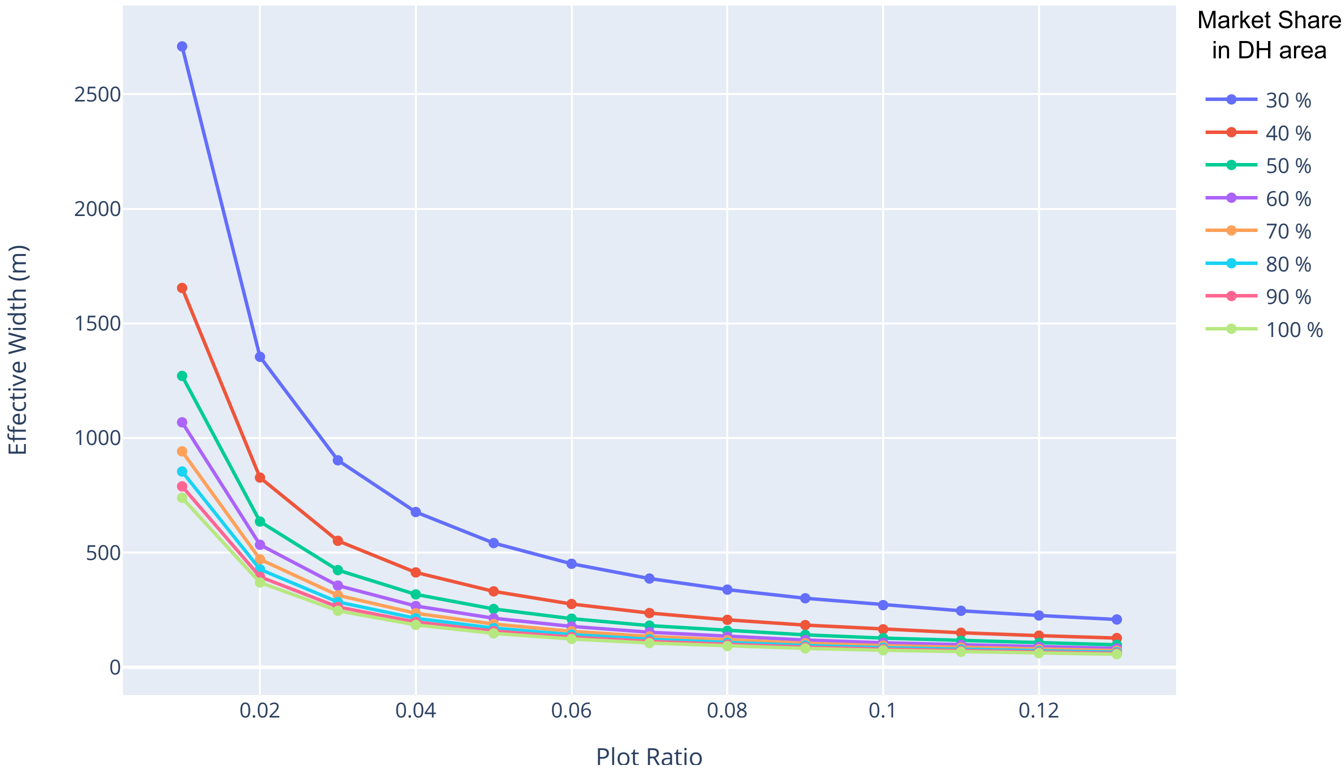

Fig. 5. Effective width of distribution pipes versus plot ratio for different DH market shares.

diameter may decrease or increase. This effect can also be seen in the average pipe diameter.

∇ (demand covered by DH) > ∇ (trench length) ➔	decrease of the DH market leads to a decrease in the linear heat density
∇ (demand covered by DH) < ∇ (trench length) ➔	decrease of the DH market leads to an increase in the linear heat density

- The impact of the DH market share in the DH areas declines as the plot ratio increases.

Fig. 7 demonstrates the relation between the specific investment costs of the DH distribution pipes and the plot ratio. Considering the specific DH distribution grid costs, the following conclusions can be drawn:

- Under a given DH market share, the specific heat distribution costs increase as the plot ratio increases.
- For a given plot ratio and a market share above 40%, the specific investment costs decrease with the increase of the DH market share.
- Although the lower market shares (below 40%) demonstrate low grid investment costs, they might not be attractive. This is because under low DH market shares DH can be implemented in fewer areas, and the heat sale volume is smaller than in the cases with high market shares. Furthermore, considering other cost components of the DH, such as heat generation costs, the overall specific costs may increase significantly.

4.1.2. Service pipes and high plot ratio area

Based on Eq. (21), a minimum adjustment factor of 0.0279 for market shares below 20% was considered. As can be seen in Fig. 8, Fig. 9 and Fig. 10, by increasing the plot ratio under a given market share, the effective width and the linear heat density increase; however, the specific investment cost decreases. At the same time, increasing the market share for a given plot ratio will increase the effective width and linear heat density and decrease the specific investment costs. However, the jumps become smaller as the market share exceeds 50%.

4.2. DH potential in EU-27 countries

The calculation for the identification of potential DH areas is conducted with an interest rate of 2% and a depreciation time of 40 years. Input parameters and obtained calculation results for the EU-27 countries are summarized in Table B.1 in the appendix of this paper. Based on the best-case scenario, the heat demand in the residential and tertiary sectors is expected to decrease by 45%, from ca. 3130 TWh in 2020 to 1710 TWh in 2050.

In 2018, EU-27 countries had a total residential area of 117,924 km^2. The identified DH areas in this paper cover 24.5% of the residential areas (=28,911.4 km^2) in the EU-27. The heat demand in the identified potential DH areas accounts for 43% and 40% of the total demand in 2020 and 2050, respectively, revealing that a large portion of heat demand in EU-27 countries belongs to the areas with high DH potential. With the increase in DH market shares, the DH potential rises from ca. 477 TWh in 2020 to ca. 531 TWh in 2050. This is equivalent to 15% and 31% of the total heat demand in the EU-27 in 2020 and 2050. Within the identified potential DH areas, up to 77% of the heat demand can be covered by DH. These results show that achieving even higher DH market shares will be possible under favorable financial and political schemes.

The total heat demand and the heat densities are relatively low in Cyprus and Malta. Implementing large DH systems in Cyprus and Malta is economically less attractive. Inside the identified DH areas in other countries, only 34.1 TWh out of 687 TWh in 2050's heat demand exists in the low plot ratio areas ($pr < 0.1353$). In terms of DH potential, it accounts for 28 TWh out of 531 TWh. Such areas are mostly in Sweden, Finland, France, Germany, Poland and the Czech Republic.

Fig. 11 illustrates the average heat densities within the identified DH

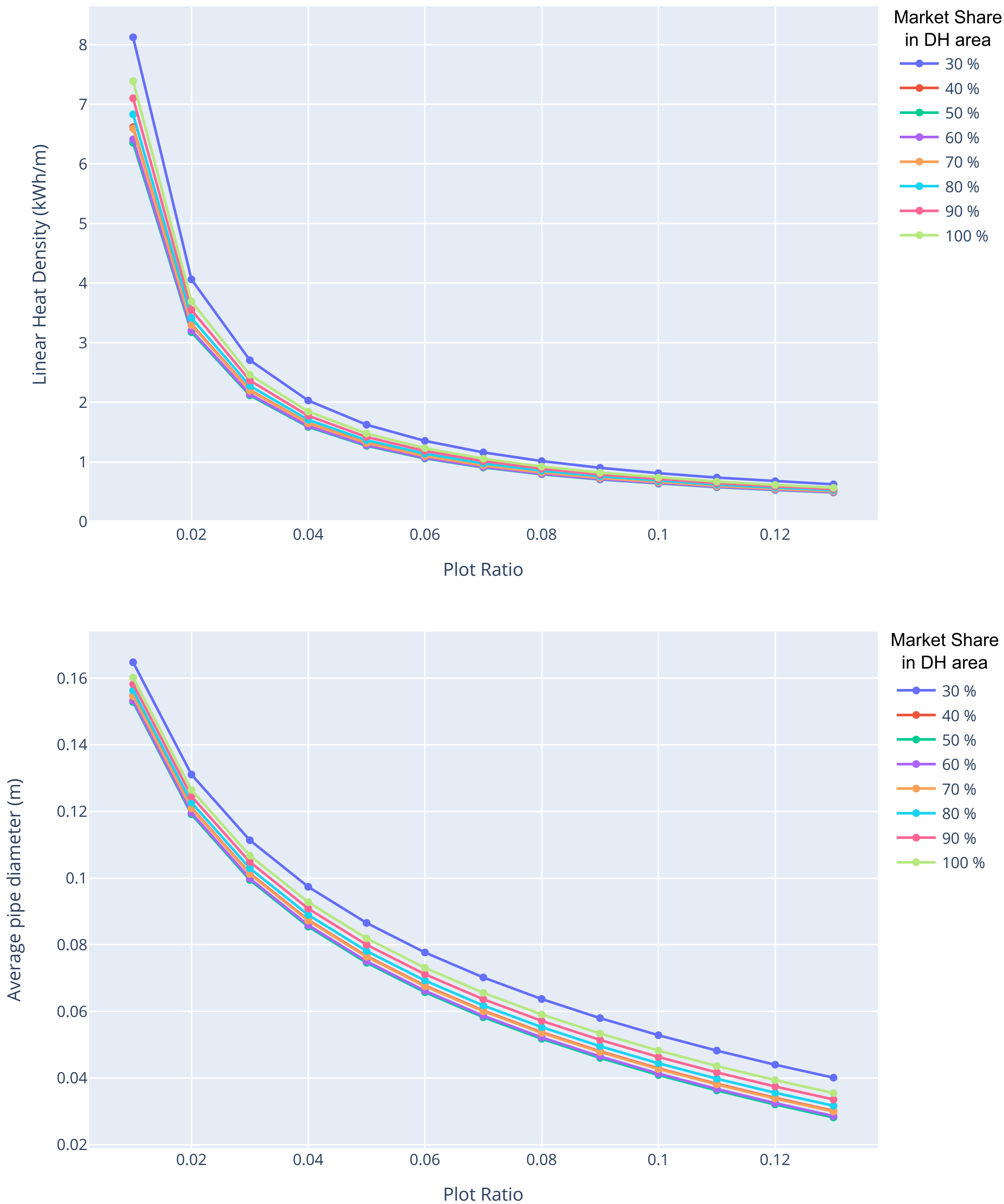

Fig. 6. Linear heat density (top) and average pipe diameter (bottom) of DH distribution pipes versus plot ratio for different DH market shares.

areas. These values are obtained by dividing the total heat demand of the identified DH areas by the sum of their areas. These numbers can be used indicatively to find coherent areas with economic potential for implementing DH. In Northern EU counties, the average heat demand density is relatively high. Therefore, even a relatively low threshold for the heat demand density in a region can be largely fulfilled and will lead to an annual heat demand favorable for the economic viability of the DH. In contrast, only high thresholds for the heat demand densities justify having a DH system in Southern EU countries, as the average heat demand densities in these countries are relatively low.

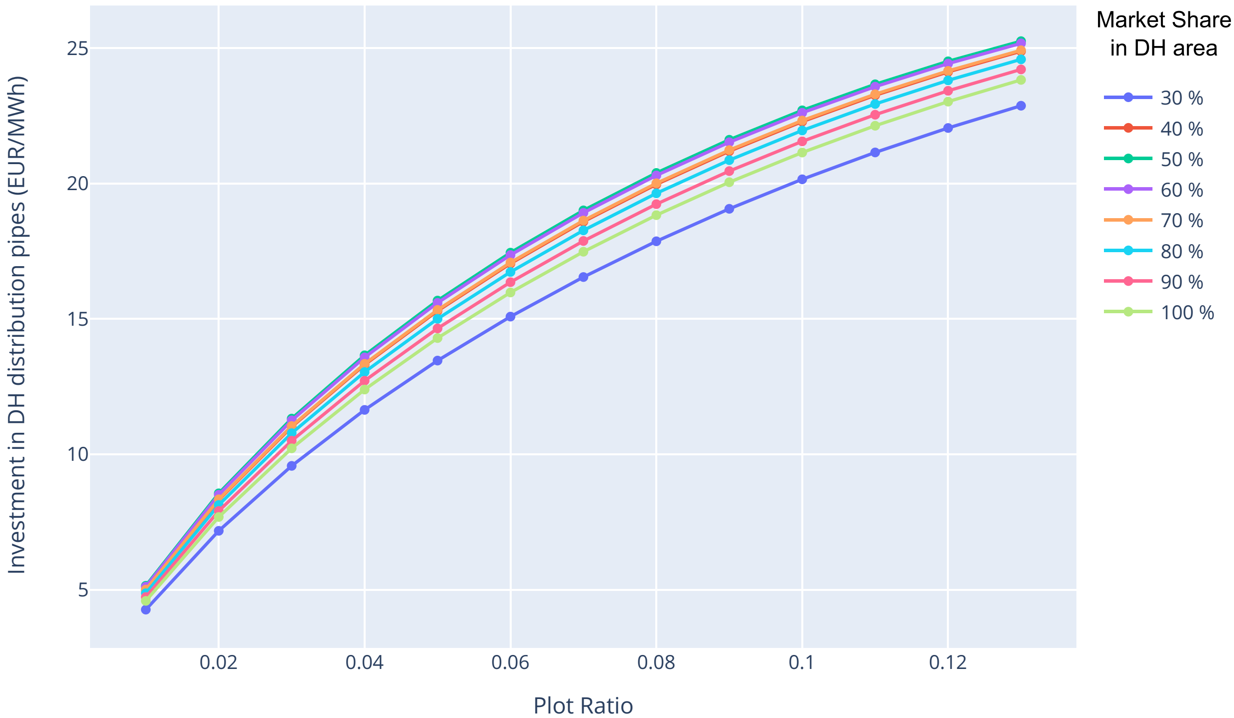

Fig. 7. Specific investment costs of the DH distribution pipes versus plot ratio for different DH market shares.

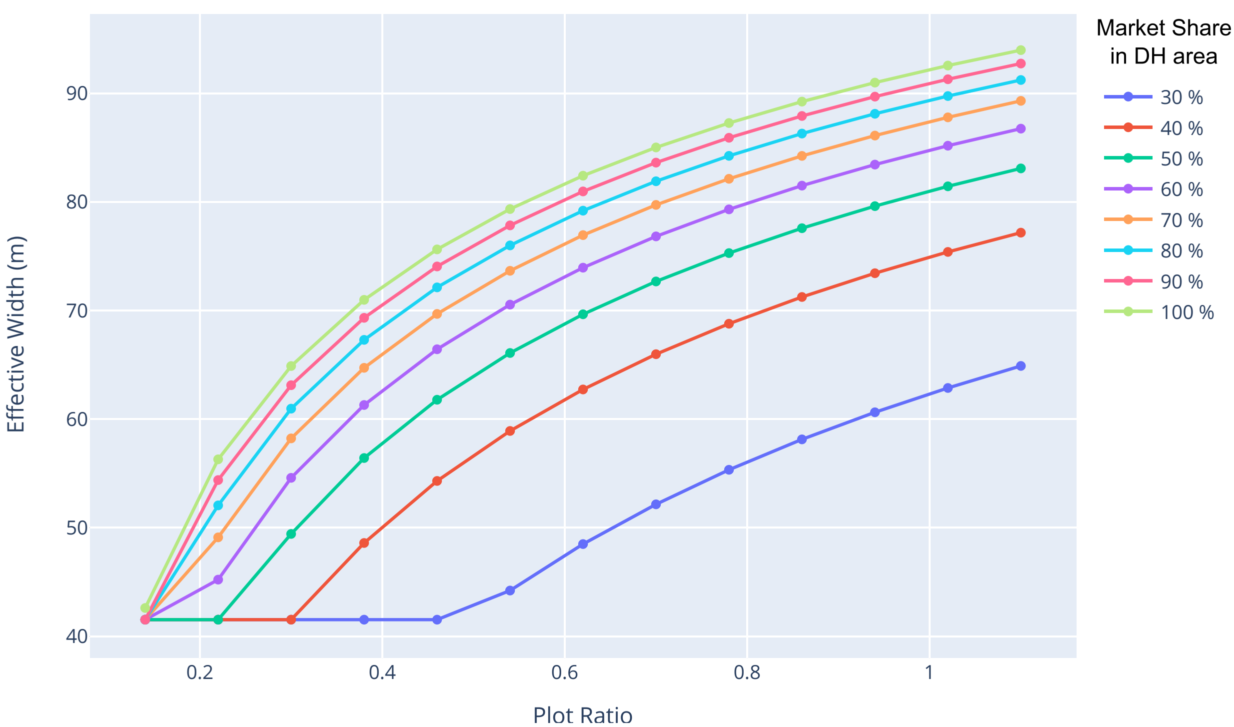

Fig. 8. Effective width of service pipes versus plot ratio for different DH market shares.

As illustrated in Fig. 11, in most member states, the average heat density is between 200 and 300 MWh/ha. Prominent exceptions are Estonia, Latvia and Lithuania, which have an average heat density below 130 MWh/ha, and Greece, Spain and Ireland, which have an average heat density of 400 MWh/ha. These values demonstrate the threshold that generally needs to be exceeded in an area of a country in order to consider it as a potential DH area. For example, an average heat demand density of 215 MWh/ha in an are within Austria is generally a necessary condition to fulfil other mentioned constraints in this paper for identifying potential DH areas.

4.3. DH grid costs

The calculations performed in this paper result in an annual investment of EUR$_{2020}$ 11.7 billion for DH grids in EU-27 countries, of which ca. 60% should flow into distribution pipes and ca. 40% into service

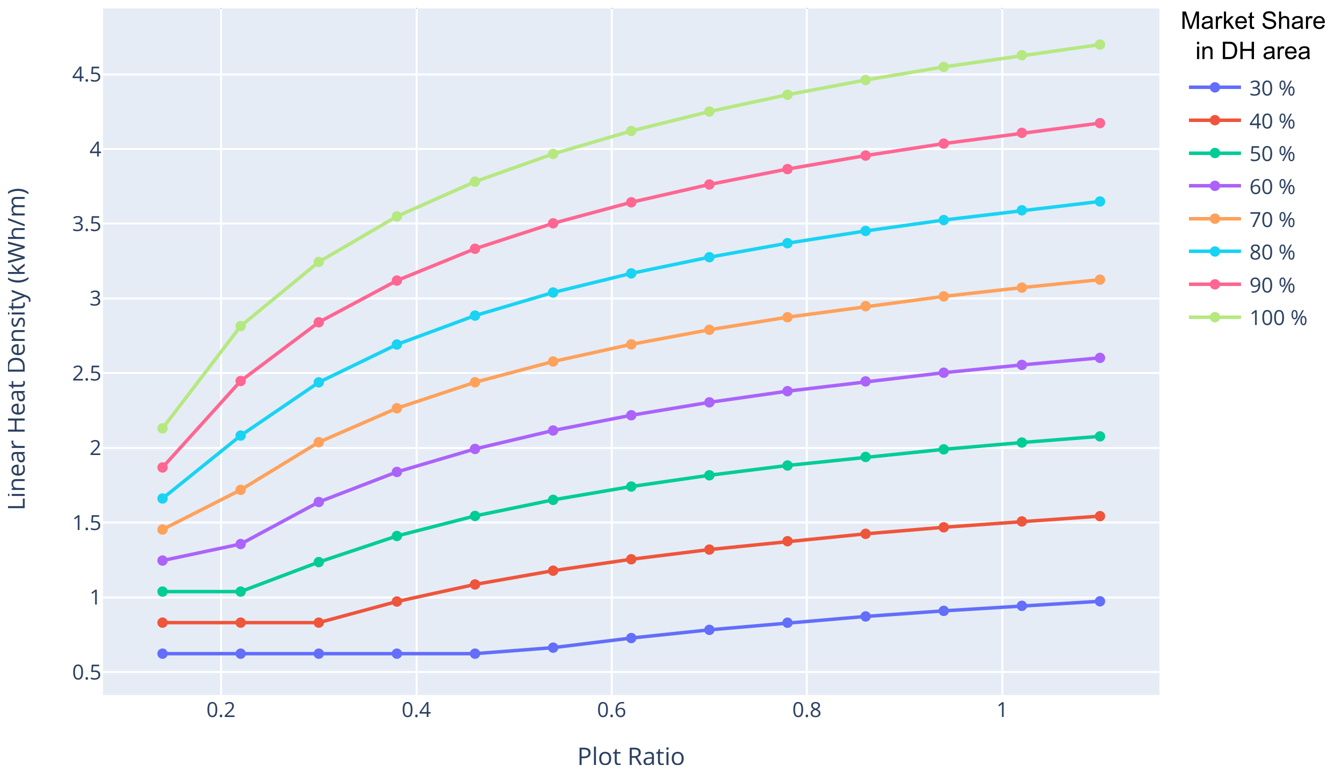

Fig. 9. Linear heat density of DH service pipes versus plot ratio for different DH market shares.

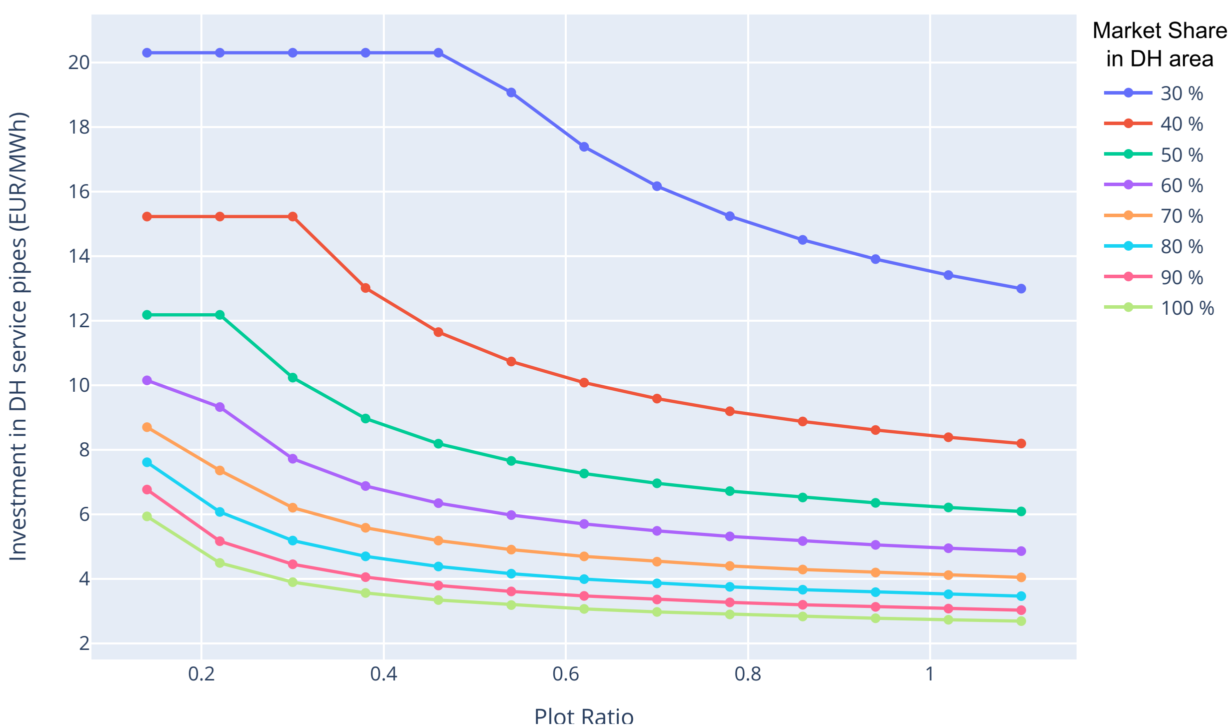

Fig. 10. Specific investment costs of the DH service pipes versus plot ratio for different DH market shares.

pipes. Table 2 summarizes the required investments in each country. If the market shares of 2050 are maintained, similar figures can be considered for the years beyond 2050.

Given a significant decrease in heat demand till 2050, expanding DH via achieving higher DH market shares is crucial for maintaining DH competitiveness. Despite the high market shares considered for 2050, as shown in Table B.1, most member states will supply less heat via DH in 2050 compared to 2020. The average specific DH grid costs are obtained by dividing the total grid costs of identified DH areas by the total delivered heat by DH from 2020 to 2050, as per Eq. (24). Accordingly,

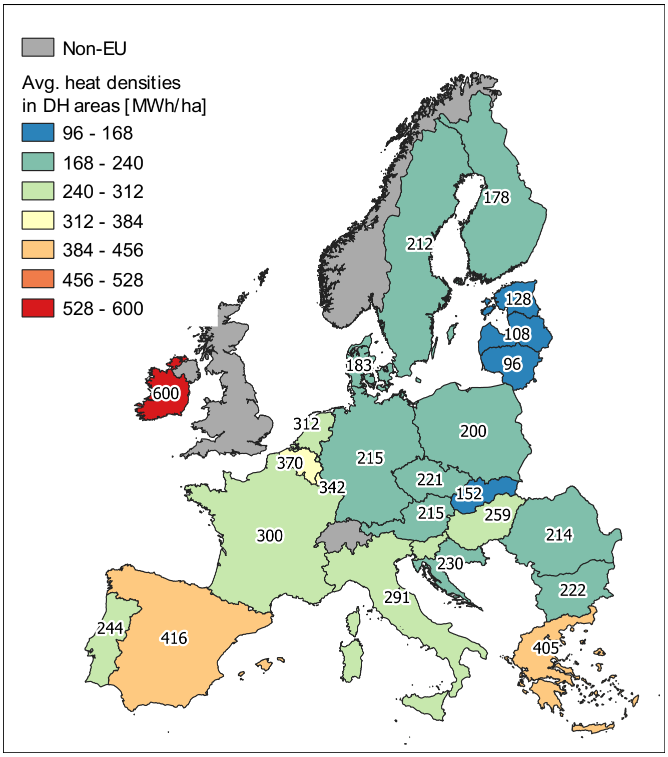

Fig. 11. Average heat densities in identified DH areas based on Best-Case scenario.

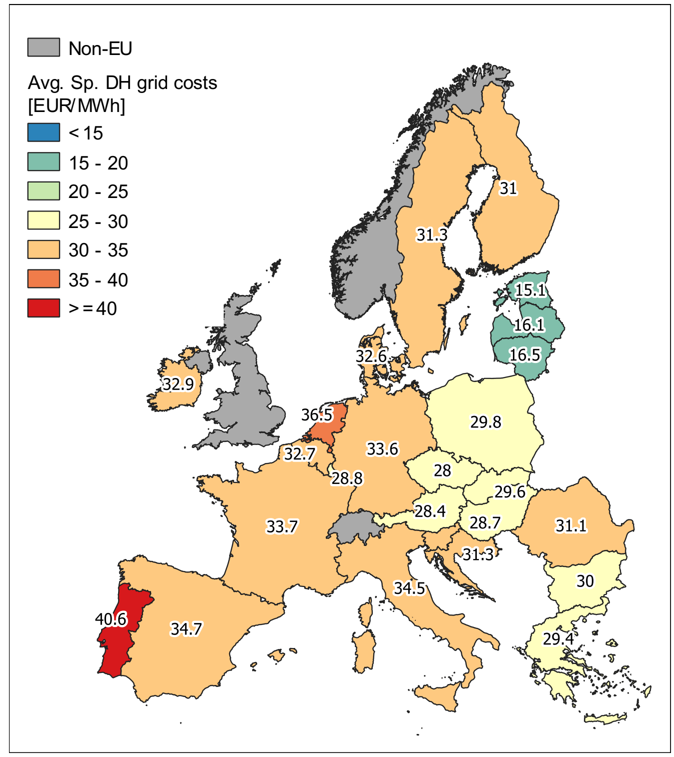

Fig. 12. Average specific DH grid costs based on Best-Case scenario.

higher starting market shares lead to lower average specific DH grid costs. Considering the inputs for the DH market shares, the average specific DH grid cost in EU-27 countries would be 31.78 EUR/MWh.

The yearly cashflows in each member state should be looked at along with the supplied heat. In that sense, specific costs provide a better picture of each member state. While average specific DH grid costs in most member states range between 28 and 32 EUR/MWh, a few countries, e.g., Estonia, Lithuania and Latvia, demonstrate lower costs due to high starting DH market shares and heat densities in DH areas. In contrast, in countries with low starting DH market shares, e.g., the Netherlands, Spain and Italy, the average specific DH grid cost exceeds 34 EUR/MWh. An overview of the average specific DH grid costs is provided in Fig. 12.

4.4. Synthesis of DH potentials and grid costs

To better understand the results, four categories of average specific DH grid costs are defined, and further analyses are conducted based on these categories.

- 0–20 EUR/MWh
- 20–30 EUR/MWh
- 30–35 EUR/MWh
- $\geq$ 35 EUR/MWh

Fig. 13 shows the share of absolute DH grid investments (EUR_{2020} 11.7 billion) and the share of 2050's DH potential (530.6 TWh/year) corresponding to each average specific DH grid cost category in the EU-27. The investment in DH areas with an average specific DH grid cost of below 30 EUR/MWh requires 25.2% of the annual investment but constitutes 31.1% of the overall DH potential in 2050. Higher average

Table 2
Yearly cashflow for investment in DH distribution and service pipes.

Country	2020 DH market share in DH areas	2050 DH market share in DH areas	Cash flow [MEUR 2020] for distribution & service pipes	Country	2020 DH market share in DH areas	2050 DH market share in DH areas	Cash flow [MEUR 2020] for distribution & service pipes
AT	55%	80%	329.9	**IE**	0%	70%	9.9
BE	15%	70%	130.8	**IT**	17%	70%	1215.6
BG	64%	75%	114.0	**LT**	78%	90%	78.1
CY	0%	0%	0.0	**LU**	29%	80%	37.5
CZ	44%	80%	443.2	**LV**	57%	80%	55.6
DE	32%	75%	2675.4	**MT**	0%	0%	0.0
DK	88%	90%	482.2	**NL**	26%	75%	384.2
EE	58%	80%	42.7	**PL**	51%	80%	1116.6
EL	29%	70%	106.7	**PT**	33%	70%	59.8
ES	3%	70%	471.2	**RO**	43%	75%	234.5
FI	63%	90%	675.4	**SE**	86%	90%	1129.0
FR	15%	75%	1461.0	**SI**	52%	80%	29.1
HR	37%	80%	57.1	**SK**	74%	90%	146.2
HU	33%	80%	248.7				
	TOTAL yearly cashflow on EU-27 level:					**11,734 MEUR**	

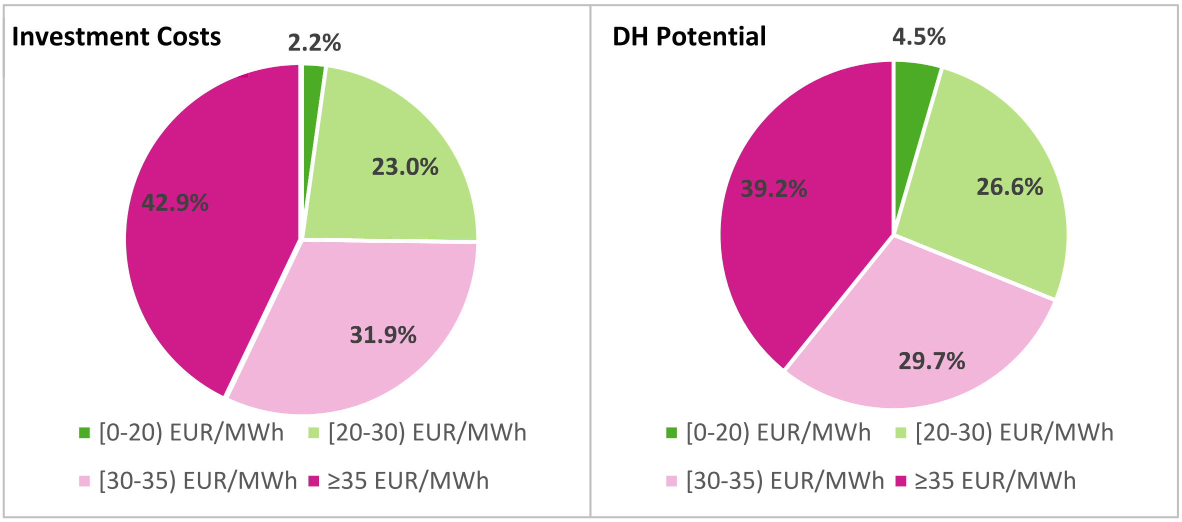

Fig. 13. Share of investment costs (left figure) and share of DH potentials (right figures) corresponding to each average specific DH grid cost category (EU-27).

specific DH grid costs result from low starting market shares or high construction costs (see Appendix) or low heat densities and plot ratios. It can also be seen that reaching the defined market shares at the EU level requires significant investment in areas with average specific DH grid costs above 35 EUR/MWh.

Fig. 14 shows the cumulative DH potential in each average specific DH grid cost category. In this figure, DH areas are sorted in ascending order based on their potential. Therefore, the slope of each curve at each point shows the amplitude of DH potential added by a region. Although a major portion of the DH potential belongs to large DH areas, especially in dense urban areas, numerous DH areas with small DH potential constitute a considerable share of the total DH potential cumulatively. All four cost categories comprise DH areas ranging from small to large DH potential. It can therefore be concluded that DH planning should not only be sought within dense urban areas, but also within small areas with lower DH potential.

The distribution of DH potential between different cost categories is not uniform in the member states. Fig. 15 illustrates the share of DH potentials corresponding to average specific DH grid cost categories in the EU member states in pie charts, putting them on top of the average specific DH grid costs provided in Fig. 12. The impact of low starting market shares, high construction costs, low heat densities, and low plot ratios can be traced in each member state.

The synthesis of the average costs depicts a favorable condition for DH expansion in Baltic and Eastern European countries. Favorable DH grid costs can also be observed in Greece and Bulgaria; however, the DH potential is relatively low in these two countries. In Denmark, Sweden and Finland, higher construction costs and market shares, besides lower heat densities, could be enumerated for average DH grid costs above 35 EUR/MWh. Low starting DH market share in identified potential DH

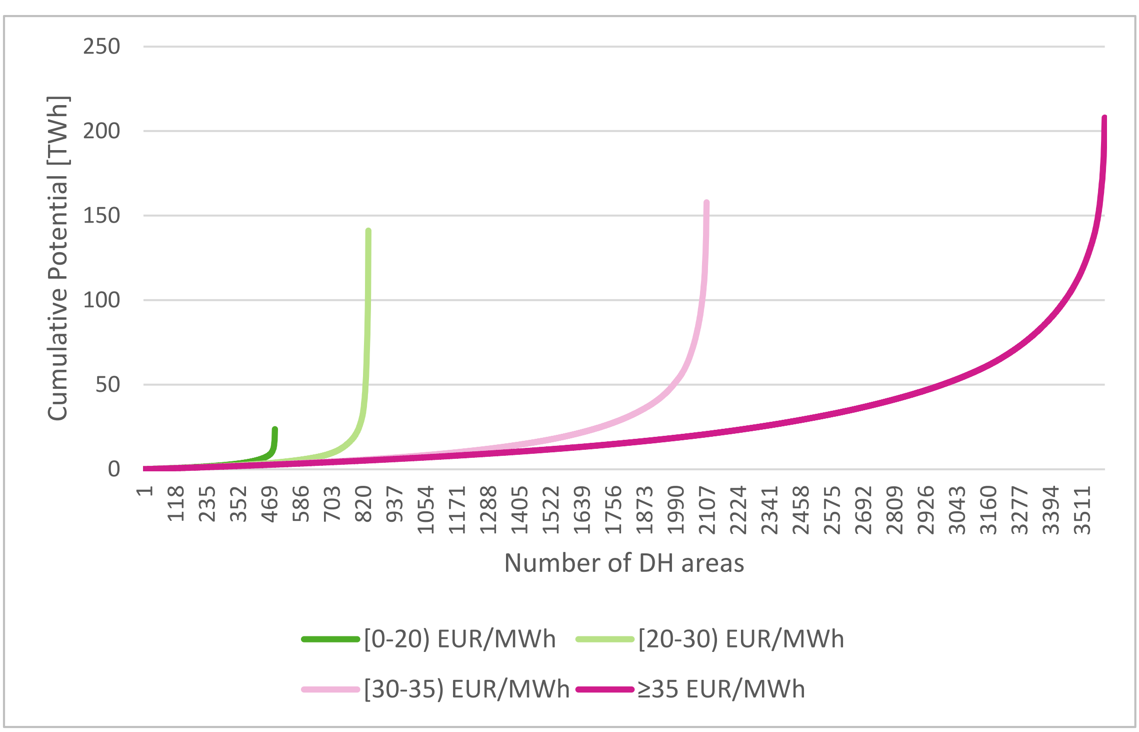

Fig. 14. Cumulative DH potential of each average specific DH grid cost category (EU-27).

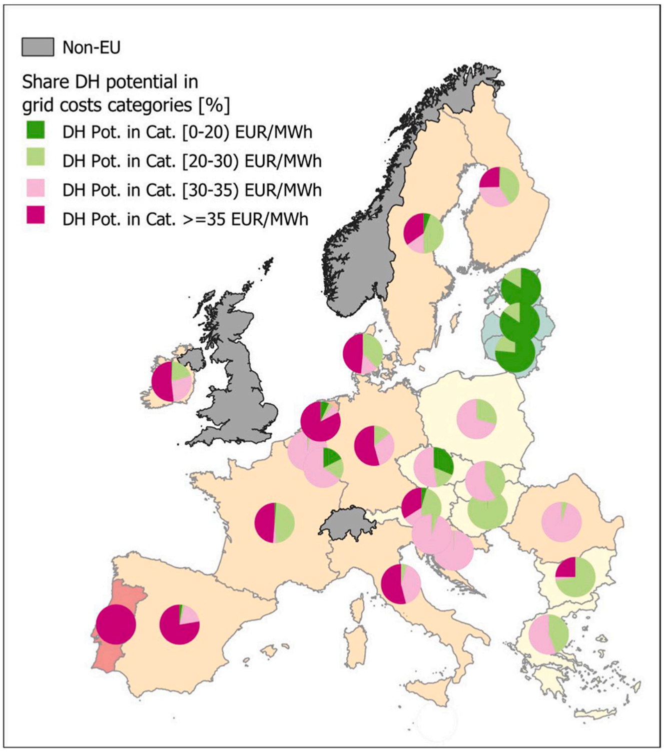

Fig. 15. Share of DH potentials corresponding to average specific DH grid cost categories in EU member states.

areas is the main reason for costs above 35 EUR/MWh in France, Italy, and Spain. In France, however, >45% of the DH potential falls in the cost category of below 30 EUR/MWh. Other member states show a mixed combination of low and high specific DH grid costs.

4.5. Impact of higher heat demand in 2050 on DH potentials

This section examines the impact of the demand reductions till 2050 on DH potential. For this purpose, the baseline scenario (BL2050) from the sEEnergies project is used [31,32]. Based on this scenario, the heat demand in EU-27 countries should reduce to 2088.7 TWh in 2050, which is 379.6 TWh higher than the estimated demand in 2050 by the best-case scenario. However, the additional 379.6 TWh heat demand is not uniformly dispersed across all regions. Under the BL2050 scenario, even slightly lower heat demand is expected for a few countries (e.g., Sweden) compared to the best-case scenario.

For the calculation, all other input data and parameters were kept unchanged. It should be emphasized that the goal of this section is solely to study the impact of heat demand levels and heat densities in 2050 on DH potential. A comparison of the scenarios is not the focus of this paper.

A summary of the obtained results for the BL2050 scenario is provided in Table B.2 in the appendix of this paper. The estimated DH potential considering BL2050's heat demands is 704.2 TWh. In absolute terms, the estimated DH potential is 173.6 TWh higher than the previous calculations. The estimated DH potential is equivalent to 34% of the total heat demand in EU-27 countries, which is three percentage points higher than the previous analysis. The average specific DH grid costs have changed at a country level, though with a mixed picture due to different distribution heat demands. On the EU-27 level, however, no changes in average specific DH grid costs were observed.

5. Discussion of results and limitations

The proposed method in this paper facilitates the study of the DH potential under various future heat demand scenarios and DH market shares. However, this entails a few assumptions:

- The heat demand and covered heat demand by DH in years between 2020 and 2050 were interpolated based on Eq. (12) and Eq. (14),
- The DH market share evolution was considered uniformly for all hectare cells of each in a country.
- For the adjustment factor:
  - o Heat supply of buildings in low plot ratio areas is conducted either with or without DH (having two or more heating systems in a building was excluded),
  - o Using an adjustment factor curve for ten buildings per hectare.
- A minimum annual DH demand of 5GWh/year was set as a criterion for identifying DH areas.

The assumptions were applied uniformly in all regions. Where possible, conservative assumptions were made to avoid overestimating the DH potential. The assumptions impose limitations in applying the results in the implementation phases but are accurate enough for the pre-feasibility and feasibility studies.

This paper also seeks to provide a realistic picture of DH potential and grid costs in low plot ratio areas by introducing an adjustment factor and using it inside the formula of the effective width (Eq. (22) and Eq. (23)). The adjustment factor allows the modeling of the impact of DH market shares. It is clear that low plot ratio areas should not be overlooked for DH planning even though their DH potential is low and their specific DH grid cost is higher. The specific cost of distribution pipes in low plot ratio areas is sensitive to the DH market share, as shown in Fig. 7; however, the specific distribution costs are close to each other at a given plot ratio. On the other hand, Fig. 10 reveals that service pipes are more sensitive to DH market shares both at low and high plot ratio areas. The specific cost of service pipes can considerably increase if high market shares are not achieved.

Various data sets are used to break down the heat demand from energy balances to hectare level. As concluded in [30], these data sets are suitable for strategic purposes on aggregated levels of larger areas and might overestimate demand in sparse areas. The 5 GWh criterion as the minimum annual DH demand in DH areas, which was used in this paper, ensures that no overestimation for DH potential is made. At the same time, this assumption neglects the areas with low DH potential.

The combination of a minimum annual DH demand of 5 GWh and a heat distribution cost ceiling guarantees that only suitable areas are identified as DH areas. For setting the heat distribution cost ceiling, as illustrated in Table B.1, the construction cost constant (C_1) and construction cost coefficient (C_2) in each country were considered. Looking at the columns for "Average specific DH grid cost in all DH areas over the lifetime" in Table B.1 shows that the cost ceilings are sufficiently relaxed for most countries. Exceptions are countries with a relatively low DH potential, like Portugal or Greece. In these cases, only a few DH areas were identified and extended up to the limit defined by the heat distribution cost ceiling.

Both best-case and BL2050 scenarios demonstrate ambitious heat demand reductions till 2050. The results show that the overall DH potential depends on the heat demand in 2050. The expansion of DH grids and achieving high DH market shares in 2050 is vital for the economic feasibility of DH, especially if ambitious demand reduction goals for 2050 are achieved. Otherwise, the existing grids might be overdimensioned for future heat demands, and the levelized cost of heat generation and distribution will be high.

For an ultimate assessment of DH potential, it is also necessary to study the supply side and availability of heat sources. However, heat generation was beyond the scope of this paper. Nevertheless, the results reported here can be used for a more detailed analysis of DH potential. A similar approach was followed by Fallahnejad et al. in their study of DH potential under climate neutrality for the case of Austria [12].

6. Conclusions

DH grids are not built all at once. The expansion of DH grids is a gradual process. This paper used the existing theoretical framework of modeling heat distribution costs of DH systems and introduced an approach for modeling the gradual heat demand reduction and evolving DH grid expansion. This approach provides a more realistic picture of the heat distribution costs and DH potential since it does not assume 100% connection rates in DH areas.

Furthermore, this paper suggests using an adjustment factor for the plot ratio for DH areas with DH market shares below 100%. The adjustment factor affects the costs of distribution pipes at low plot ratio areas ($pr \leq 0.1353$) and service pipes under all plot ratio ranges and provides a conservative estimation of costs. The impact of the adjustment factor on distribution and service pipes was elaborated in two examples. It was shown that at a given plot ratio, the cost of the service pipes is affected more heavily by DH market shares than distribution pipes.

An updated assessment of the DH potential across the EU member states, considering the future development of both heat demand and DH market share within DH areas, was presented. The calculations were performed for two different scenarios: The best-case scenario from a report on "renewable space heating under the revised Renewable Energy Directive" published by the European Commission [4] and the baseline scenario (BL2050) from sEEnergies project [31]. The result of the latter scenario was used to check the impact of higher heat demands in 2050 on DH potential.

In the decarbonization scenario (best-case scenario), heat demand in EU-27 countries will decrease by 45% by 2050. Under this condition, maintaining the existing grid infrastructure while covering lower heat demand with DH will increase specific grid prices. To avoid high grid costs, DH grids should be expanded in economically favorable areas, and supply levels should be maintained or increased. In this paper, the expected DH market shares defined for each member state for 2050 were considerably higher than their 2020 levels. Despite high DH market shares in 2050, DH potential can increase by only 11% by 2050 compared to 2020. A yearly investment of 11.7 billion Euros at the EU level is required to expand the DH grid under this scenario.

The result of the calculations for the BL2050 scenario showed three percentage points higher potential (34%) compared to the best-case scenario. The average specific heat distribution costs were slightly different from the best-case scenario; however, on the EU-27 level, they remained unchanged. This result highlights the importance of expanding DH grids and achieving sufficiently high DH market shares within DH areas. This is achievable under favorable financial and political support schemes, such as DH zoning, for DH.

CRediT authorship contribution statement

Mostafa Fallahnejad: Conceptualization, Data curation, Formal analysis, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Lukas Kranzl:** Supervision, Writing – review & editing. **Reinhard Haas:** Supervision, Writing – review & editing. **Marcus Hummel:** Conceptualization, Validation. **Andreas Müller:** Data curation. **Luis Sánchez García:** Conceptualization, Methodology, Validation, Writing – review & editing. **Urban Persson:** Writing – review & editing, Conceptualization, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The input and output data are provided in [38].

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Appendix A

Table A.1 shows the construction cost constants and coefficients in different EU-27 countries. These values are obtained from the sEEnergies project [24]. Where sEEnergies do not provide the data, coefficients from the most similar countries have been used. These countries are distinguished by an asterisk (*).

Table A.1
construction cost constants and coefficients in the EU-27 member states.

Country	C1 [EUR/m]	C2 [EUR/m2]	Country	C1 [EUR/m]	C2 [EUR/m2]
DE	349	4213	IE*	549	2236
AT*	349	4213	IT	349	4213
BE*	549	3370	LT	71	3262
BG*	349	4213	LU*	549	3370
CY*	540	2087	LV*	71	3262
CZ*	349	4213	MT*	540	2087
DK*	439	4073	NL	549	3370
EE*	71	3262	PL*	349	4213
EL*	540	2087	PT*	354	4314
ES	354	4314	RO*	349	4213
FI*	439	4073	SE	439	4073
FR*	349	4213	SI*	540	2087
HR*	349	4213	SK*	349	4213
HU*	349	4213			

Appendix B

Input parameters and obtained calculation results for the EU-27 countries for the best-case and BL2050 scenarios are summarized in Table B.1 and Table B.2, respectively.

Fill color	Description
	Input
	Output
	EU-27
	Not Relevant/Applicable

Table B.1
Summary of input and output parameters obtained for the **best-case scenario.**

Country	Demand [TWh]		Changes in demand [%]	DH market share in DH areas		Heat distribution cost ceiling [EUR/MWh]	Average specific DH grid cost in all DH areas over the lifetime [EUR/MWh]	Demand in identified DH areas [TWh]		Share of demand in DH areas from total demand in the country [%]		DH potential [TWh]		Share of DH potential from total demand in the country [%]	
	2020	2050		2020	2050			2020	2050	2020	2050	2020	2050	2020	2050
AT	84.2	43.1	-49%	55%	80%	36.0	28.4	36.8	16.9	44%	39%	20.3	13.6	24%	31%
BE	115.2	47.4	-59%	15%	70%	33.6	32.7	24.0	8.7	21%	18%	3.6	6.1	3%	13%
BG	24.3	14.3	-41%	64%	75%	38.4	30.0	9.6	6.4	40%	45%	6.2	4.8	25%	33%
CY	2.7	2.6	-3%												
CZ	92.3	51.9	-44%	44%	80%	34.8	28.0	50.2	27.0	54%	52%	22.1	21.6	24%	42%
DE	805.8	356.4	-56%	32%	75%	36.0	33.6	342.6	140.2	43%	39%	109.6	105.1	14%	29%
DK	58.8	35.2	-40%	88%	90%	39.6	32.6	32.9	17.0	56%	48%	29.0	15.3	49%	43%
EE	12.5	5.9	-53%	58%	80%	36.0	15.1	9.1	3.8	72%	65%	5.3	3.1	42%	52%
EL	38.5	29.4	-23%	29%	70%	31.2	29.4	12.2	8.9	32%	30%	3.5	6.2	9%	21%
ES	145.7	111.0	-24%	3%	70%	36.0	34.7	61.0	45.3	42%	41%	1.8	31.7	1%	29%
FI	76.6	43.0	-44%	63%	90%	37.2	31.0	56.8	29.4	74%	68%	35.8	26.5	47%	62%
FR	487.5	303.4	-38%	15%	75%	40.8	33.7	192.7	105.5	40%	35%	28.9	79.1	6%	26%
HR	25.2	10.1	-60%	37%	80%	32.4	31.3	7.0	3.0	28%	29%	2.6	2.4	10%	23%
HU	80.0	40.4	-49%	33%	80%	30.0	28.7	31.3	16.0	39%	39%	10.3	12.8	13%	32%
IE	34.0	21.7	-36%	0%	70%	36.0	32.9	1.3	1.2	4%	5%	0.0	0.8	0%	4%
IT	383.4	223.2	-42%	17%	70%	36.0	34.5	159.9	88.4	42%	40%	27.2	61.9	7%	28%
LT	17.4	9.1	-48%	78%	90%	32.4	16.5	10.9	5.9	63%	65%	8.5	5.3	49%	59%
LU	7.8	4.3	-45%	29%	80%	32.4	28.8	5.1	2.6	65%	61%	1.5	2.1	19%	49%
LV	15.4	6.3	-59%	57%	80%	32.4	16.1	11.1	4.7	72%	74%	6.3	3.7	41%	59%
MT	0.8	0.9	11%												
NL	135.6	72.2	-47%	26%	75%	38.4	36.5	41.8	23.0	31%	32%	10.9	17.3	8%	24%
PL	244.2	121.1	-50%	51%	80%	31.2	29.8	124.0	54.7	51%	45%	63.2	43.8	26%	36%
PT	27.9	20.0	-29%	33%	70%	40.8	40.6	4.8	3.5	17%	17%	1.6	2.4	6%	12%
RO	83.8	37.1	-56%	43%	75%	32.4	31.1	27.8	12.3	33%	33%	12.0	9.2	14%	25%
SE	86.2	77.8	-10%	86%	90%	42.0	31.3	64.9	55.1	75%	71%	55.8	49.6	65%	64%
SI	12.2	6.8	-44%	52%	80%	31.2	30.8	2.9	1.5	24%	22%	1.5	1.2	12%	17%
SK	30.8	14.5	-53%	74%	90%	32.4	29.6	13.0	5.7	42%	39%	9.6	5.1	31%	35%
EU-27	**3,128.8**	**1,709.1**	**-45%**				**31.8**	**1,333.6**	**686.6**	**43%**	**40%**	**476.9**	**530.6**	**15%**	**31%**

Table B.2
Summary of input and output parameters using 2050's heat demands from the sEEnergies project (**BL2050**).

Country	Demand [TWh]		Changes in demand [%]	DH market share in DH areas		Heat distribution cost ceiling [EUR/MWh]	Average specific DH grid cost in all DH areas over the lifetime [EUR/MWh]	Demand in identified DH areas [TWh]		Share of demand in DH areas from total demand in the country [%]		DH potential [TWh]		Share of DH potential from total demand in the country [%]	
	2020	2050		2020	2050			2020	2050	2020	2050	2020	2050	2020	2050
AT	84.2	49.1	-42%	55%	80%	36.0	27.4	38.4	24.8	46%	50%	21.1	19.8	25%	40%
BE	115.2	72.1	-37%	15%	70%	33.6	33.0	32.1	21.1	28%	29%	4.8	14.8	4%	20%
BG	24.3	26.2	7%	64%	75%	38.4	32.2	11.7	13.1	48%	50%	7.5	9.8	31%	38%
CY	2.7	1.5	-45%												
CZ	92.3	52.6	-43%	44%	80%	34.8	30.5	49.3	26.6	53%	51%	21.7	21.3	24%	40%
DE	805.8	451.8	-44%	32%	75%	36.0	33.1	400.7	242.3	50%	54%	128.2	181.7	16%	40%
DK	58.8	51.9	-12%	88%	90%	39.6	30.4	35.7	29.8	61%	57%	31.4	26.8	53%	52%
EE	12.5	9.8	-22%	58%	80%	36.0	13.6	9.2	6.5	73%	66%	5.3	5.2	43%	53%
EL	38.5	24.5	-36%	29%	70%	31.2	31.1	9.9	6.8	26%	28%	2.9	4.8	7%	20%
ES	145.7	213.1	46%	3%	70%	36.0	33.6	76.3	105.8	52%	50%	2.3	74.0	2%	35%
FI	76.6	49.3	-36%	63%	90%	37.2	28.7	48.3	31.8	63%	64%	30.4	28.6	40%	58%
FR	487.5	309.1	-37%	15%	75%	40.8	35.9	193.7	105.0	40%	34%	29.1	78.8	6%	25%
HR	25.2	10.5	-58%	37%	80%	32.4	32.0	4.0	1.1	16%	10%	1.5	0.9	6%	8%
HU	80.0	44.3	-45%	33%	80%	30.0	29.2	27.1	12.7	34%	29%	8.9	10.2	11%	23%
IE	34.0	15.5	-54%	0%	70%	36.0	35.5	0.1	0.0	0%	0%	0.0	0.0	0%	0%
IT	383.4	308.7	-19%	17%	70%	36.0	33.4	182.9	147.7	48%	48%	31.1	103.4	8%	33%
LT	17.4	12.7	-27%	78%	90%	32.4	16.8	10.9	7.0	62%	55%	8.5	6.3	49%	49%
LU	7.8	5.4	-31%	29%	80%	32.4	31.9	4.1	2.4	52%	44%	1.2	1.9	15%	35%
LV	15.4	15.6	1%	57%	80%	32.4	12.9	11.5	10.5	75%	67%	6.6	8.4	43%	54%
MT	0.8	1.0	17%												
NL	135.6	93.2	-31%	26%	75%	38.4	37.8	32.2	16.0	24%	17%	8.4	12.0	6%	13%
PL	244.2	123.4	-49%	51%	80%	31.2	29.5	115.9	59.4	47%	48%	59.1	47.5	24%	39%
PT	27.9	17.3	-38%	33%	70%	40.8	39.6	2.4	1.3	8%	7%	0.8	0.9	3%	5%
RO	83.8	39.8	-52%	43%	75%	32.4	31.6	21.9	8.8	26%	22%	9.4	6.6	11%	17%
SE	86.2	66.2	-23%	86%	90%	42.0	32.0	53.5	37.6	62%	57%	46.0	33.9	53%	51%
SI	12.2	8.2	-33%	52%	80%	31.2	30.3	2.8	2.0	23%	24%	1.4	1.6	12%	19%
SK	30.8	15.9	-48%	74%	90%	32.4	30.7	12.8	5.7	42%	36%	9.5	5.2	31%	32%
EU-27	**3,128.8**	**2,088.7**	**-33%**				**31.8**	**1,387.2**	**925.7**	**44%**	**44%**	**477.0**	**704.2**	**15%**	**34%**

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