sEEnergies

QUANTIFICATION OF SYNERGIES BETWEEN ENERGY EFFICIENCY FIRST PRINCIPLE AND RENEWABLE ENERGY SYSTEMS

D4.5

District heating investment costs and allocation of local resources for EU28 in 2030 and 2050

This project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No 846463.

Project

Acronym	**sEEnergies**
Title	Quantification of Synergies between Energy Efficiency First Principle and Renewable Energy Systems
Coordinator	Brian Vad Mathiesen, Aalborg University
Reference	846463
Type	Research and Innovation Action (RIA)
Programme	HORIZON 2020
Topic	LC-SC3-EE-14-2018-2019-2020 - Socio-economic research conceptualising and modelling energy efficiency and energy demand
Start	01 September 2019
Duration	34 months
Website	https://seenergies.eu/

Consortium	**Aalborg Universitet (AAU)**, Denmark **Hogskolan i Halmstad (HU),** Sweden **TEP Energy GmbH (TEP),** Switzerland **Universiteit Utrecht (UU),** Netherlands **Europa-Universität Flensburg (EUF),** Germany **Katholieke Universiteit Leuven (KULeuven),** Belgium **Norges Miljø- og Biovitenskapelige Universitet (NMBU),** Norway **SYNYO GmbH (SYNYO)**, Austria **Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung e.V. (Fraunhofer),** Germany

Deliverable

Number	**D4.5**
Title	**District heating investment costs and allocation of local resources for EU28 in 2030 and 2050**
Lead beneficiary	EUF
Work package	WP4
Dissemination level	Public (PU)
Nature	Report (RE)
Copyright license	CC BY 4.0
Due date	28.02.2021
Submission date	15.03.2021
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Document history

Version	Date	Comments
0.1	01.03.2021	Draft version sent to reviewers
0.2	12.03.2021	Reviewed version
1.0	15.03.2021	Final version for submission
1.1	12.05.2021	Final version for submission, Eq. 4 corrected

Acknowledgement: This project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No 846463.

Disclaimer: The content of this publication is the sole responsibility of the authors, and in no way represents the view of the European Commission or its services.

Executive Summary

Efficiency in the heat sector and the built environment can be achieved by building retrofits, the replacement of buildings, and the development of district heating as a means of structural energy efficiency. Hereby, excess heat and low-grade renewable heat sources can be integrated in the heat sector. The present report describes the future heat sector of Europe from end-use via infrastructure to heat sources. Future heat demands on national level have been modelled by sEEnergies project partners. In the present work, these demands are being distributed to future urban areas. Population forecasts have been combined with local empirical data to new 100m resolution population grids. They form the basis for the calculation of heat demands for the years 2030 and 2050 on the same geographical level. Potential areas, where district heating could be developed, have been zoned as prospective supply districts (PSDs) and basic statistics of heat demand have been calculated. Then, based on empirical district heating network data from existing district heating networks in Denmark, a new investment cost model for distribution and service pipes has been developed. Based on previous work in the Heat Roadmap Europe research project, the cost model has been improved with a better understanding of the concept of effective width. With the integration of country-specific construction cost data this results in an improved district heat distribution capital cost model for all Member States of the European Union plus the United Kingdom. The spatially explicit combination of district heat potentials and costs results in cost-supply curves for all countries as the basis for the assessment of the economic potential of future district heating. Finally, available excess heat sources from industry, waste incineration, wastewater treatment plants, and current powerplant locations are being allocated to prospective supply districts. Renewable heat potentials, including deep geothermal heat, solar thermal heat, and residual, local biomass, have also been assigned to these prospective heat supply areas. The results of the present work have been published as a web map.

URL to D4.5 Datasets Web-App:

D4.5 Datasets Web-App (arcgis.com)

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Acronyms & Abbreviations

Term	Description
DH	District heating
e	Plot Ratio (pr) a.k.a. Building Density [-]
GIS	Geographical Information Systems
GJ	Gigajoule
HD	Heat demand
HRE4	Heat Roadmap Europe 4
kJ	Kilojoule
MWh	Megawatt hour
NUTS	Nomenclature of Territorial Units for Statistics (*Nomenclature des unités territoriales statistiques*)
Peta	Pan-European Thermal Atlas
PSD	Prospective Supply District
w	Effective Width [m]
WP	Work package

1 Introduction

The demand and supply of heat is a major component in present and future energy systems of Europe. About 50% of the final energy demand is associated to the heating sector (EC, 2016a). The analysis of efficiency in the built environment is therefore essential. This includes energy efficiency measures in buildings, as well as "structural" energy efficiency by means of district heating and the use of excess heat and low-grade heat from renewable energy sources.

The present report is an account of the activities in work package 4 (WP4) of the sEEnergies project under the headline "District heating investment costs and allocation of local resources for EU28 in 2030 and 2050". In order to assess the potentials and costs of future district heating networks, future heat demands must be modelled at high geographical resolution. For distribution capital cost modelling, local floor area plot ratios and heat demand densities must be mapped as the basis for economic assessments of district heat potentials. Potential locations of district heating grids must be found and delineated in order to quantify the heat demands to be supplied from networks and assign locally available excess and renewable heat supply options.

District heating is most feasible in areas with high heat demand densities and densely populated urban structures, despite the fact that heat distribution costs in such inner-city areas often are affected by relatively higher construction costs due to existing infrastructures. However, future district heating of the 4th generation (4DH) systems, i.e. low-temperature systems, are expected to also supply heat to areas where extensive efficiency measures have reduced heat demand densities and where heat from low-grade sources can be supplied to consumers at lower forward temperatures.

In the sEEnergies project, scenarios which describe country-specific pathways for reducing the heat demand of a continuously growing building stock in Europe, are used to assess heat demand densities for the future years of 2030 and 2050. Economic growth and the resulting accumulation of building floor space, as well as energy efficiency measures, have been established in work package 1 (WP1) of the project, and form the basis for these assessments. These are important parameters for the technological and economic feasibility of thermal grids.

The result of this work is a set of numerical and geospatial datasets, which on local, regional, and national levels describe the sequence from heat demand to heat provision: from useful heat demand in residential and service sector buildings via heating grid infrastructures to locally and regionally available heat sources. The data is made available on Web-App maps (see Figure 1) and forwarded to the project consortium, primarily work package 6 (WP6), as tabular data.

1.1 Objectives and scope

The main objective of WP4 in the sEEnergies project is to analyse the behaviour and costs of different energy grids: electricity, thermal and gas grids; as well as energy storage solutions. The results and outputs from WP4 will primarily serve as input for WP6, where final energy system modelling of the respective sectorial (buildings, transport, and industry) energy efficiency potentials will be performed. As a secondary objective, WP4 will assess the feasibility and technological constraints of the scenarios (current and future for 2030 and 2050) towards a full decarbonisation in Europe. The findings will be combined into resource-economic quantitative assessments of opportunities and constraints for the implementation of energy efficiency in the heating sector in the EU regions.

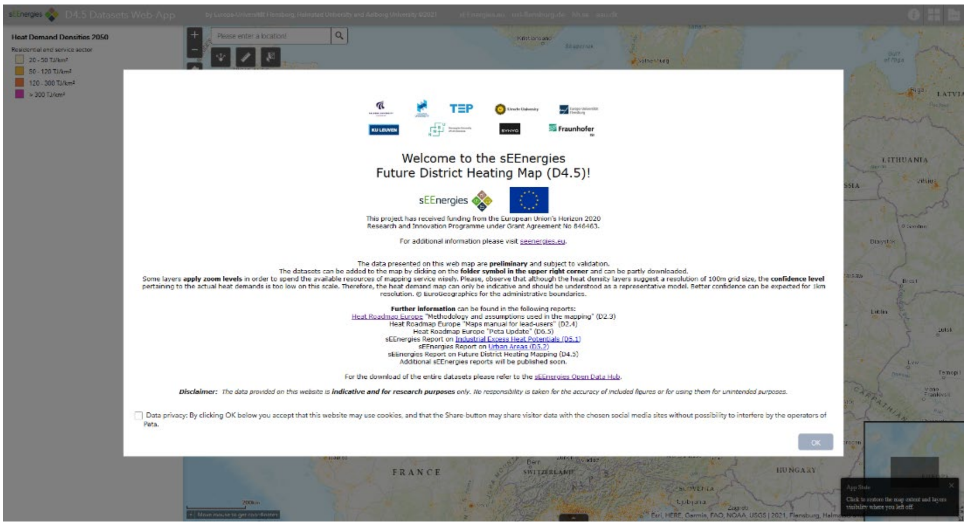

Figure 1. Welcome screen at the sEEnergies D4.5 Datasets Web-App. Source: (Wiechers, Möller, Persson, & Sánchez-García, 2021).

The WP4 work on thermal grids addresses all the current 27 EU member states plus the United Kingdom, for which the physical and economic suitability for district heating is analysed for the current year (2015) and two future year settings (2030 and 2050). While this report focusses explicitly on the two future year settings, the results and findings for the current year scenario are reported in the D4.4 deliverable report of WP4.

In addition, a third account, the D5.7 deliverable report (Spatial models and spatial analytics results) scheduled for project month 30 (February 2022), will complete our three-step publication strategy for the WP4 work on thermal grids by providing the full methodological background and final output versions of the future year mapping.

1.2 Preliminary character of presented results

Due to the iterative nature of the work process in the sEEnergies project, especially so regarding the interchange of input data between different work packages in combination with the outlined dissemination of numerical and cartographic material from work package 5 (WP5) in two main modules; one for current year mapping (D5.3) and another for future year mapping (D5.5), the character of the presented results in this report is to be considered as preliminary.

As presented here, a first set of future year results and outputs have been produced, however, we expect that during the coming year (leading up to the final reporting of future year mapping results in the project), these outputs may be subject to updates, corrections, and other improvements based on continuous refinements and developments of our used approaches and models. Therefore, we kindly ask our readers to bear this in mind, when reading this account and to take notice of the upcoming deliverables, by which final versions of these future assessments will become available.

2 Underlying heat demand assumptions for the scenario years 2030 and 2050

Spatially distributed heat demands for space heating and domestic hot water preparation in residential and service sectors constitute the primary basis for estimating investment costs for district heating networks. In previous work, see e.g. (Urban Persson, Wiechers, Möller, & Werner, 2019), the density of heat demands per hectare is used to express the “physical suitability” for district heating. Together with economic parameters, such as construction costs and annuity (further described in section 3), heat demand densities establish an empirical basis for infrastructure cost assessments, which for the current year (2015) is reported in the sEEnergies project context in the D4.4 report (Cost and capacity analysis for representative EU energy grids depending on decarbonisation scenarios). For future years, however operational data are not yet available. The assessment of future heat demand densities therefore constitutes the main challenge and an important contribution to this work.

Future heat demand and its geographical distribution is a function of the development of the building stock and its energy properties, of the expansion of urban areas, of demographic change, and the policies and planning practice. It is therefore intrinsically complex. The spatial distribution of future population is here assumed to follow current population patterns. It is subjected to demographic change, movements, intra-urban development, as well as the development of future settlement areas.

Using national population forecasts from the PRIMES model, combined with WP1 projections of heat demands and floor areas on country level, future heat demands are distributed to the 1-hectare level by modelling future population per hectare, and allocating building space and its heat demand accordingly.

A model has been developed to forecast the future development of population and settlements. Future national heat demands have been distributed to these, and resulting heat demand densities, prospective supply districts and district heating infrastructure costs have been calculated. The results are to be used for energy systems analysis in WP6.

2.1 Population distributions based on settlement developments

Across the EU, land use and physical practices, the speed at which urban areas are developed, and the rate at which land is consumed are very different. Following the energy efficiency first principle, dense settlements are favourable; and from a biodiversity and environmental point of view, the fragmentation of landscapes and the sealing of land should be avoided.

The distribution of past and current population has been mapped by the Global Human Settlement layer, GHS, by the JRC (Joint Research Centre) of the EU Commission (Schiavina, Freire, & MacManus, 2019). The data is available as multitemporal grids of 250m resolution, which has been resampled to 100m resolution using bilinear interpolation, as illustrated for the case of the Öresund region (centred around the Danish capital Copenhagen and the Swedish city of Malmö) and two different years (1990 and 2015) in Figure 2. The population grids were derived by distributing small area statistics from sources like the Gridded Population of the World (Center for International Earth Science Information Network, 2019) to built-up area grids derived from remote sensing.

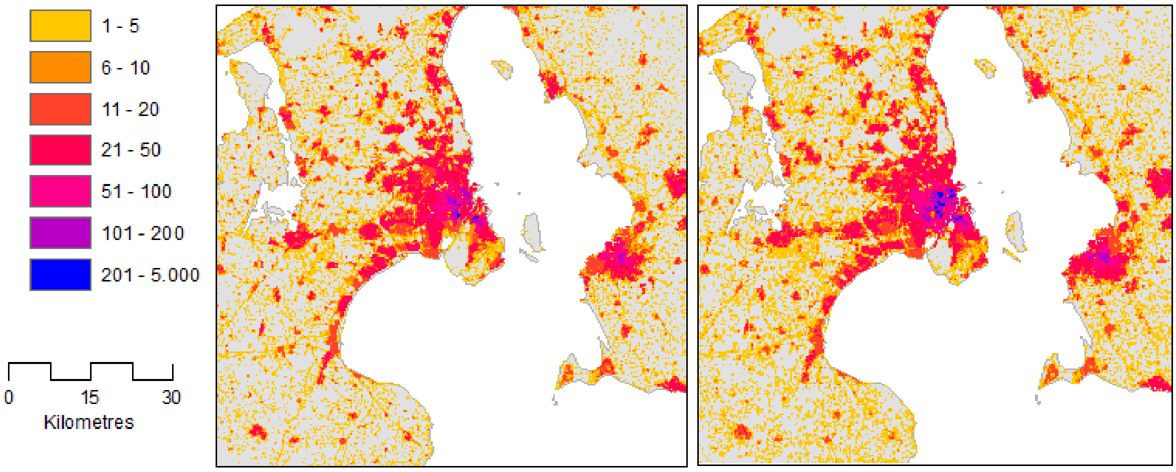

Figure 2. Population grids from the Global Human Settlement Layer, resampled to 100m resolution. Left: population 1990, right: population 2015. The population increment, positive or negative, forms the basis for the local population development.

In a simplified but functional process, the expansion of existing settlements follows a morphological approach. In raster-based analysis applying geographical information systems (GIS), focal statistics calculate the characteristics of the neighbourhood of each populated cell. For this purpose, the 70th percentile population increment value of all cells in a neighbourhood defined by a radius of 300m (for 2030) and 200m (for 2050) is calculated. These neighbourhood statistics, found by experiment, transfer the past development in a local area to potential new build areas next to them. If the increment is positive, this leads to a potential settlement area and its suggested population density, which is calculated by the annual increment and the time span between scenario years. The percentile function favours areas with a high existing population density. It seeks to increase this while reducing the demand for new settlement areas. Negative population increments in the past lead to a continued de-population, as can be seen in many rural districts of Europe, but also in many city centres in Eastern Europe.

Suitable land for the expansion of urban areas is mapped using the CORINE land cover database in its 100m raster version (European Environment Agency, 2018). Excluded from future urban developments are artificial surfaces (CLC 1xx), forests and semi-natural areas (CLC 3xx), wetlands (4xx), and water bodies (5xx). This leaves agricultural areas (2xx) as suitable areas. While conservation areas like NATURA2000 are not considered here, there is little overlap to potential urban areas, as very few of them include agricultural land near settlements. Arguably, this method could be improved by including other suitability and protection criteria, and by allowing conversion of non-urban fabric already developed, such as former industrial areas. All suitable areas get the raster value 1, while the non-suitable areas are coded with the value 0.

The future population increment depends on the current settlement status. If an area is already built up, the past population development defines the future trend. In areas not yet developed, and in the urban fringe, which is generally less densely populated, the future population density is a combination of the past trend, its neighbourhood distribution, and the availability of land.

The population of the year 2030 is calculated in a first iteration using the 1990-2015 trend and the extent of settlements as per the GHS population layer in the year 2015. It is proportionally adjusted to the national population forecast of the PRIMES (2016) model (EC, 2016b). In a second iteration, the

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modelled 2030 population grid forms the outline of settlements in that year, and the further expansion of urban areas towards the year 2050 is driven by the modelled development from 2015 to 2030. The land cover outside areas which are expected to be populated until 2030 is assumed to be the same as in 2018.

The additional requirement of building space, and hence land space, is indirectly considered using the data from WP1 for calculating the plot ratio, albeit with uncertainty attached. The demand for new settlement locations is driven by the past local development and the national population forecast. The model allocates new population to existing areas when these have managed to attract new inhabitants in the past. Also, new settlements appear near areas, which have attracted new dwellers in the last decades. Urban areas that have seen a population decline, will continue to do so in the future.

In general, there is a trend of rural to urban migration, which will continue for most of Europe. Overall, the future population model is a first attempt in a future population forecast at 100m resolution for all the EU member states, and it delivers a basis for the calculation of future heat demands.

2.2 Heat demand distribution based on population development and specific heat demand developments

Future heat demands and their geographical distribution are assumed to follow small scale population patterns on the 1-hectare level and in neighbourhoods of 0.1 to 0.3 km², which is a usual size of local development plans. As the GHS layer is based on the mapping of built-up areas, the population grids derived from it can be used to distribute heat demands. A simplified approach distributes the sum of the national heat demands of the residential and service sectors to all areas identified as populated by the intensity of population.

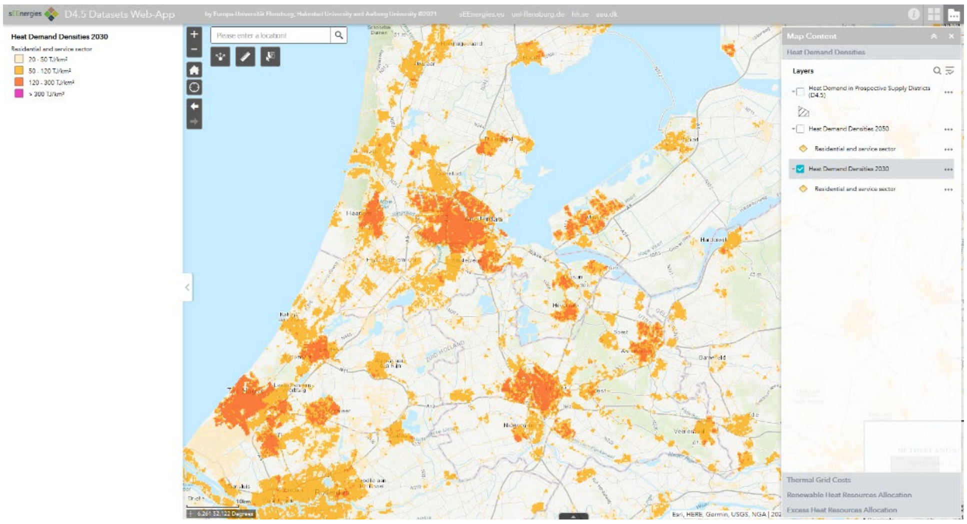

Figure 3. Screenshot from the D4.5 Datasets Web-App with active operational layer: Heat demand densities in 2030 for the Amsterdam region in the Netherlands.

In other words, the 2030 and 2050 heat demand densities [GJ/ha], as illustrated in Figure 3 and Figure 4 for the Amsterdam region in the Netherlands for 2030 and 2050 respectively, are proportionally distributed to the hectare level by multiplying the modelled hectare population with the ratio of national heat demand and the national population, both derived from the PRIMES model. Subsequently, the heat demands are corrected for climatic variation within a country by the National Heating Index (Werner, 2006) developed in the Heat Roadmap Europe project.

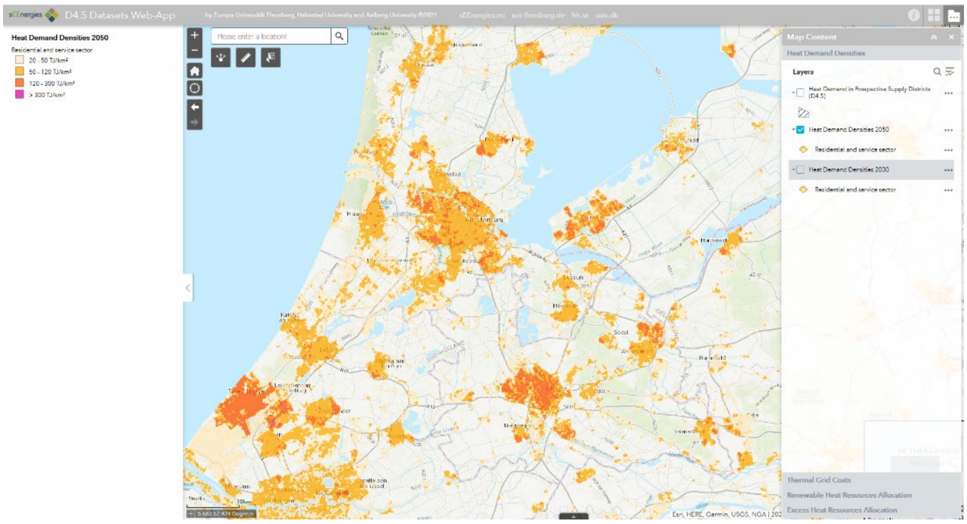

Figure 4. Screenshot from the D4.5 Datasets Web-App with active operational layer: Heat demand densities in 2050 for the Amsterdam region in the Netherlands.

The simplification is justified by the impossibility to precisely locate future populations, building densities, and building properties with the geographic extent of the EU. The future heat demand grids are therefore a representative model case only, which largely is based on locally derived past trends, a rudimentary assessment of the neighbourhood of urban areas for future expansion, which disregards actual policies, and following the national population and floor area developments derived in the PRIMES model as well as the work done in WP1.

For overview reference, the output from this approach is a result of anticipated counteracting effects from e.g. continued urbanisation and population growth (relative a total EU28 population count in 2015 of 505 million, the PRIMES 2016 reference model scenario indicates a 2.1% increase by 2030 (516 million) and a 3.3% increase by 2050 (522 million)), and continued reductions of building heat demands due to refurbishments, energy savings, increasing annual average ambient temperatures etc. As a general indicator, albeit Member State variations exist, the EU28 total useful residential and service sector heat demand is reduced in 2030 by 8.6%, relative the 2015 reference year, and is anticipated at some 10.5 EJ in this work. Similarly, the 2050 heat demand for this sector is found at approximately 8.7 EJ (a reduction of 24.8% relative the 2015 reference year).

3 District heating investment costs for 2030 and 2050

District heating investment costs for the two future years 2030 and 2050 are calculated on the conceptual basis inherent to the distribution capital cost model first presented by Persson and Werner in (Urban Persson & Werner, 2011), later to be further developed by the authors in (Urban Persson et al., 2019). The key model output, the marginal distribution capital cost, C_d (euro/GJ), is the product of an annuity factor, a (-), here representing an economical lifetime of 30 years and a real interest rate of 3%, and the quota of specific investment costs and linear heat density, as expressed in Equation 1:

$$C_d = a \cdot \frac{\left(\frac{I}{L}\right)}{e \cdot q \cdot w} = a \cdot \frac{(C_1 + C_2 \cdot d_a)}{q_L \cdot w} \quad \left[\frac{€}{GJ}\right] \qquad \text{(Eq. 1)}$$

The numerator, i.e. the specific investment cost (I/L), may be characterised by a linear function determined by an intercept C_1 (construction cost constant (€/m)) and a slope C_2 (construction cost coefficient (€/m^2)) which is multiplied with the average system pipe diameter, d_a (m), as modelled by use of its previously established relation to linear heat density. As further described in section 3.1.2 below, the construction cost terms are established in this work based on nation-specific data where this has been available, which is a considerable improvement compared to previous model assessments where EU average terms were used.

The denominator, i.e. the linear heat density, may be characterised as the product of heat demand density, q_L (J/m^2), and effective width, w (m). Both if these denominator terms are subject to improvements in this work. Firstly, as described above, the heat demand densities of future European urban areas and settlements are assessed by a sequential approach of combining underlying data on expected and anticipated developments regarding for example population and urbanisation growth, floor areas, plot ratios, and the corresponding mapping of their future distribution. Secondly, as further described in section 3.1.1 below, a special in-depth study has been performed in this work in order to establish a better understanding of the behaviour of effective width, particularly in so called "low plot ratio" areas, i.e. settlement areas characterised by low heat demand densities but where opportunities for future district heating systems still may exist due to clustering of sparse settlements.

The distribution capital cost is established as the marginal cost but also expressed as the average cost (which is done by accumulating all costs and heat demands possible to supply at each marginal cost level). The costs reflect annual payback on investment capital for the piping system buried into the ground in current year monetary value. Resulting cost curves are established for EU27 plus United Kingdom as grand total curves for the entire EU, but also on national, regional, and local levels.

Notably, where all previously published outputs from the used model have entailed costs for district heat distribution pipes only – district heating systems ordinarily consisting of three pipe types: transmission; distribution; and service pipes – the outputs from this work include total costs for investments in both distribution and service pipes. By this model extension, which is believed to add further practical value to the results, anticipated cost levels are not intuitively comparable to previous reports since they are the sum of costs for both these pipe categories.

For the communication in this report, EU and Member State results are presented in section 3.2 in the form of marginal and average cost curves. Outputs on the regional level (NUTS3 regions) have been stored in the form of tabular data (.csv files) but are not further presented here. The main purport of these regional results is to provide input for the energy system modelling in WP6.

3.1 Key methodological improvements and features

Capital costs for district heating networks have been estimated on a hectare level for all the EU28 Member States. Unlike the Heat Roadmap Europe project model results, this deliverable provides not only the capital costs for distribution pipes but also the capital costs for service pipes[1], which, in low density areas in particular, may account for half of the total pipe length and hence, a significant part of the total capital cost.

The determination of the capital costs of district heating networks is based on the model developed previously by (Urban Persson & Werner, 2011). This model has as main input the linear heat density, which may be estimated as the product of the area heat demand and the effective width. Furthermore, it requires a linear equation, which provides the installation costs of district heating pipes for different diameters. The obtention of these two model parameters is explained in further detail in the following two sub-sections.

In addition to the technical aspects of deploying a district heating network (pipe length and diameter), the model also considers the amortization of the network over its economic lifetime. This has been achieved using the Equal Instalment Method, whereby the sum of interest and principal remains constant through the amortization period. An economic lifespan of 30 years at an interest rate of 3% results in an annuity of 5.1%.

3.1.1 Effective width

The effective width is the ratio between the ground area and the pipe length. From this parameter, it is possible to estimate the linear heat density. Previous work (Urban Persson & Werner, 2010, 2011; Urban Persson et al., 2019) has related this parameter to the so-called plot ratio ("pr", quotient between floor area and ground area) or building density. However, the relations were based on a very limited set of examples and only included distribution pipes. An extensive analysis of a large Danish district heating system (that in the city of Odense, 3rd largest city in Denmark with a population of approximately 0.18 million in 2019) has enabled establishing new relations for both distribution and service pipes with a more solid empirical base. Moreover, an initial objective for this analysis of effective width was to have it performed upon the basis of uniform land area units, as those of raster grids, which was not the case in previous work (Urban Persson & Werner, 2010).

The data for this analysis has been provided by Fjernvarme Fyn (Rasmussen & Hansen, 2020) and it has been complemented by building data stemming from the Danish Building Register (Bygnings- og Boligregisteret (BBR), 2018) and the Danish Agency for Data Supply and Efficiency Improvement (Styrelsen for Dataforsyning og Effektivisering, 2021). For the former, the data has consisted in a geographical representation of the entire district heating system in the city of Odense, in the form of shape files with attributes such as pipe type, pipe diameter etc. For the latter, the data has consisted in geocoded buildings and parcels, with information on e.g. floor areas by building type and sector etc.

For the analysis, a sequence of steps, arranged and executed in the form of scripts using the R programming language, was arranged by which the data was managed, stored, and structured, as described in the following steps:

[1] These pipes connect each individual building to the main pipelines, which serve a number of buildings. However, costs for installation of heat exchangers in connected buildings are not included in the calculated costs.

1. Establishment of a regular quadrangular grid covering the entire district heating network. The cell area was set to one hectare.
2. Determination for each cell of the grid the pipe length and the average diameter for the three types of pipes: transmission, distribution, and service, using as input the Geographic Information System (GIS) containing Fjernvarme Fyn's network.
3. Building a GIS with the buildings' floor area (including the residential and service sectors) from BBR and the cadastre parcels from the Danish Agency for Data Supply and Efficiency Improvement.
4. Determination of the total floor area in each cell of the grid. In the common case of a building occupying more than one cell, the floor area of the building has been projected to each cell according to the proportion of the parcel's area in the cell.
5. Calculation of the plot ratio in each cell as quotient between the floor areas of the buildings and the ground areas.
6. Creation of a database with the previous values (pipe length, average diameter, and plot ratio) for each cell of the grid.
7. Analysis of the database at different levels of geographical aggregation, i.e., grouping the information of contiguous cells.

The last step has been the most challenging since two factors affect the optimal cell size with opposite trends. On the one hand, a smaller cell size is beneficial since it allows for a better characterization of the urban fabric and the sharp boundaries between urban and non-urban areas. On the other hand, a larger grid cell permits a better linkage between pipe length and the urban environment. For instance, with a small cell size, one cell may contain a lot of buildings and barely pipes and the neighbouring cell the opposite and this problem disappears with increasing cell size. The balance of these two trends has led to a compromise with a cell size of 2 500 m^2, which has resulted into the data points depicted in Figure 5 for distribution (left) and service pipes (right), respectively.

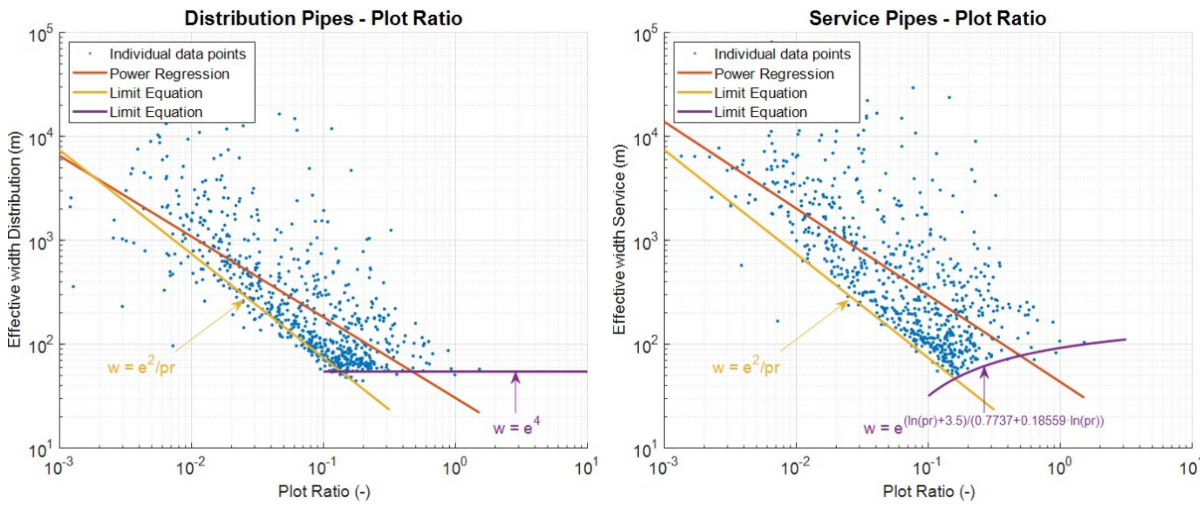

Figure 5. Effective width as a function of plot ratio; for distribution pipes as left and for service pipes at right.

Using these data points, various regression models were evaluated, whereof the most promising was found to be a power regression. Unfortunately, none of the models delivered a perfectly satisfactory result with different issues such as non-normality of residuals. In this situation, a practical approach was decided, taking advantage of the circumstance that the lower bound of the effective width for different plot ratios follows rather sharp edges, as observable in Figure 5. Instead of taking the average effective width for a given plot ratio, the minimum value was chosen. This guarantees that the actual effective width value will almost always be higher than the estimated value and consequently, the pipe length, and hence the cost, will be consistently overestimated. The effective width for a given plot ratio is therefore calculated in the model using the following equations, which are also indicated in the respective graphs in Figure 5:

- Hyperbola in the very low plot ratios of both distribution and service pipes:

$$w = \frac{e^2}{pr} \quad [m] \qquad \text{(Eq. 2)}$$

- Constant effective width for higher plot ratios in the case of distribution pipes:

$$w = e^4 \approx 55\,m \qquad \text{(Eq. 3)}$$

- Hyperbola in the log-log scale for high plot ratios in the case of service pipes

$$w = e^{\frac{\ln(pr)+3.5}{0.7737+0.18559\cdot\ln(pr)}} \qquad \text{(Eq. 4)}$$

These equations do not provide the average value of the effective width for a given plot ratio but, rather, the minimum value the effective width may take, and hence, they may be seen as conservative estimates for the effective width. Consequently, the calculated linear heat densities with these equations will be generally lower than the actual linear heat densities and the capital costs will, in turn, be overestimated.

3.1.2 Construction costs

The construction cost of a district heating pipe is impacted by a series of parameters such as the total length of the pipe (the longer, the lower the unit cost), the type of surface (cheaper in new developments or green areas) or the presence of existing infrastructure (gas, water, electrical or sewage networks). Therefore, there exists a great deal of variability between projects and an accurate appraisal of the construction cost of a new system would require detailed knowledge of all these variables and local labour conditions. Since this type of information is not available on a general basis, only cost curves using the pipe diameter as sole variable have been utilised here. In those rare cases in which more than one pipe cost curve was available for different areas, the most conservative curve has been taken in order to remain on the safe side.

Heat Roadmap Europe used the same construction costs for district heating pipes for the entire set of countries under analysis (Urban Persson et al., 2019). However, an important factor in the overall cost is the civil works component in which labour could play a significant role. This issue and the fact that the source for Heat Roadmap Europe's costs was Sweden, one of the countries with the highest labour costs of the continent, could artificially endanger the viability of district heating in other countries. To illustrate this potential source of variation in Member State construction costs for district heating systems, although not further elaborated in the modelling in this context, Figure 6 shows national labour costs as reported by Eurostat for industry, construction, and services sectors, and as indexed by the corresponding Swedish labour cost levels. It is quite clear that the cost of labour varies significantly among the Member States. However, national variations in this work were derived only indirectly with reference to labour costs, as they are implicit in average national construction cost curves.

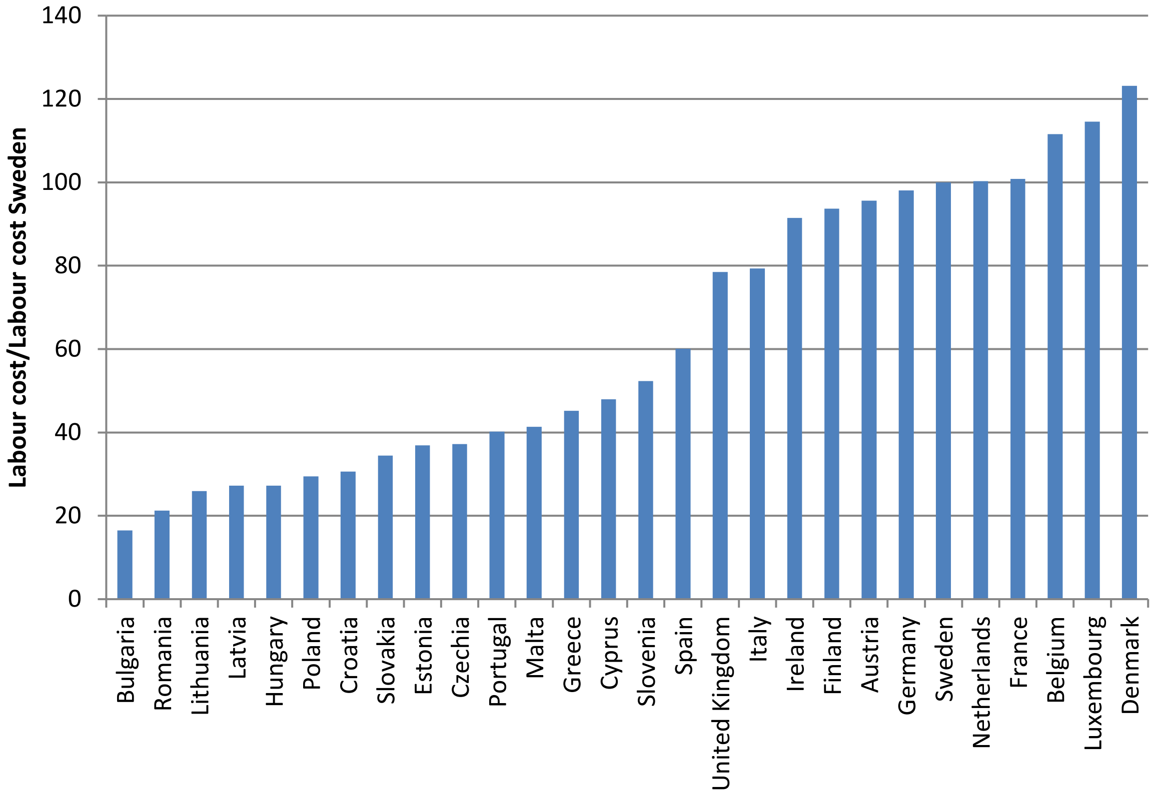

Figure 6. Index of labour costs in the Industry, construction, and services sector by country with respect to Sweden in 2019. Source: Eurostat.

National data on construction cost curves for district heating systems were sought and found in ten Member States, as outlined in Table 1, which summarises the information gathered from these countries, along with the sources for them. In addition, Table 2 indicates which country's data has been utilised in case a construction cost curve could not be obtained for the country in question. The general rule for the allocation has been to use the most similar country based on distance and labour cost.

Table 1. Construction cost curve parameters for ten European Countries[2]

Country	Range validity (pipe diameter [mm])		Intercept	Slope	Source
	Min	Max	€/m	€/m²	
Germany	25	300	349	4213	(Besier, Klöpsch, & Wagner, 2009)
Spain	65	125	354	4314	(Cuesta, 2020)
France	65	450	*	*	(Roger, 2020)
Croatia	25	250	*	*	(Dorotić, 2020)
Italy	50	400	540	2087	(Denarie, 2020)
Lithuania	70	600	71	3262	(Gurklienė, 2020)
Hungary	25	200	*	*	(Edit, 2020)
Netherlands	65	250	549	3370	(Schepers et al., 2019)
Sweden	50	400	439	4073	(Sánchez-García, 2017; Svensk Fjärrvärme AB, 2007)
United Kingdom	25	500	549	2236	(AECOM et al., 2017)

[2] Three countries have provided data (France, Croatia, and Hungary), but their corresponding construction cost curve parameters cannot be published due to confidentiality agreements.

Table 2. Source of national data on construction cost curve parameters used for countries from which it was not possible to obtain corresponding information

Country	Country used
Austria	Germany
Belgium	Netherlands
Bulgaria	Hungary
Cyprus	Italy
Czechia	Hungary
Denmark	Sweden
Estonia	Lithuania
Finland	Sweden
Greece	Italy
Ireland	United Kingdom
Latvia	Lithuania
Luxembourg	Netherlands
Malta	Italy
Poland	Hungary
Portugal	Spain
Romania	Hungary
Slovakia	Hungary
Slovenia	Croatia

The general conclusion which can be drawn from an analysis of these national construction cost curves, is that unit labour does not play a significant role in the overall installation cost. Only two countries, Croatia and Lithuania, present significantly lower installation costs than the rest. This contradicts the a priori assumption that unit labour costs would play a major role. On the other hand, these values should be taken with caution as they only represent an average level, and there exists a great deal of variability within a country depending on different characteristics such as total pipe length or type of surface (e.g., pavement vs green areas).

The values collected represent the costs for current systems, which are mostly a mix of 2nd and 3rd generation systems. The cost of 4th generation district heating networks' pipes is extremely difficult to estimate since a series of parameters intervene in the end result with opposite effect. On the one hand, the employment of plastic pipes, viable with the lower temperatures of the 4th generation (Lund et al., 2014; Lund et al., 2018), could reduce the cost of the materials, although the pipes themselves only account for 40%-50% of the total costs in Sweden. On the other hand, these low-temperature systems may have lower temperature differences, which would call for bigger diameters. Furthermore, labour cost in the construction sector may rise faster than general inflation as construction is largely insulated from international competition but, on the contrary, efficiency gains may be reaped. Given the uncertainty of all these issues, it was decided to utilise the pipe costs as they have been collected and assume that they would not undergo any significant change in the forthcoming decades.

With the above-described model improvements and features, the model was arranged within a GIS model builder interface accessing the plot ratio and heat demand density grids developed for 2030 and 2050, as described in section 2 above, and with a few incorporated default values: for grid cells with heat demand densities above zero and calculated linear heat densities below 1.5 GJ/m, pipe diameters were set to 0.02 meters (all cells with values at and above according to Eq. 7 in (Urban Persson et al., 2019)). Service pipe diameters were set to 0.03 meters in cells at and above 1.5 GJ/m.

3.2 Distribution capital costs for 2030 and 2050

The results from the modelling of investment costs for district heating in 2030 and 2050 are shown in this sub-section in the form of maps and graphs. The results are also available as web maps at the sEEnergies D4.5 Web-App ((Wiechers et al., 2021). In Figure 7 (2030) and in Figure 8 (2050), overview continental maps show the spatial distribution of marginal distribution capital costs at the hectare level by five discrete costs levels: below or at 1 euro per Gigajoule, between one and two euro per Gigajoule, between two and five euro per Gigajoule, between five and ten euro per Gigajoule, and finally above 10 euro per Gigajoule.

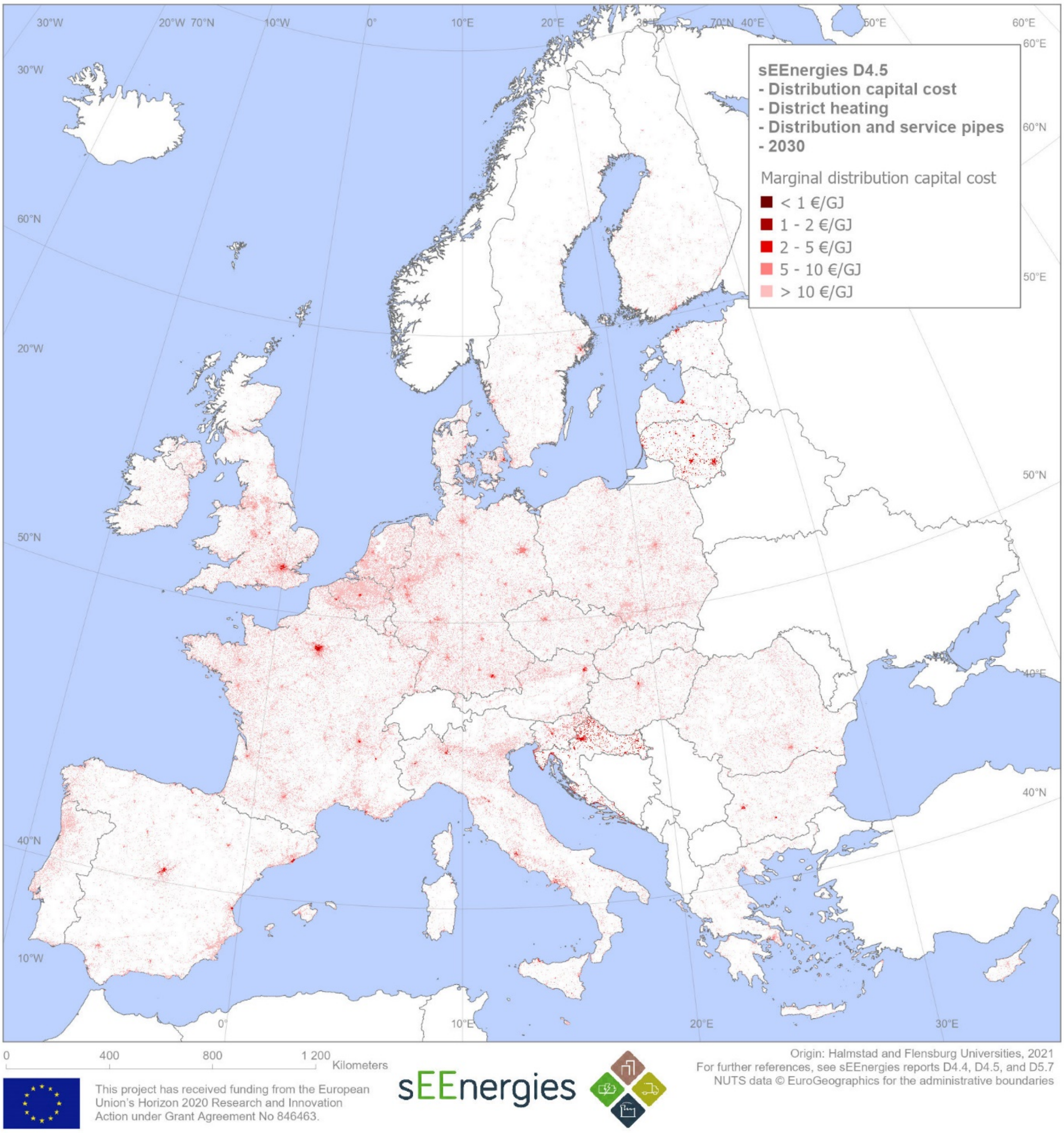

Figure 7. sEEnergies D4.5 overview map: Marginal distribution capital costs for the EU27 Member States plus United Kingdom in 2030, by hectare level including costs for both distribution and service pipes.

At this overview level, proper justice is not made to the very high level of detail by which these results have been generated. However, Figure 7 and Figure 8 provides a first order conception of the actual spatial spread and locations of the most beneficial large urban and metropolitan areas in Europe where investments in district heating should be most feasible. As has been previously recognised, inner city areas in particular, provide beneficial conditions for cost-effective network heat distribution, and, as it appears in this modelling, these conditions are not expected to change significantly in the coming ten years leading up to 2030. From 2030 and onwards, however, in the period leading up to 2050, our results indicate a change in such conditions towards increased general cost levels.

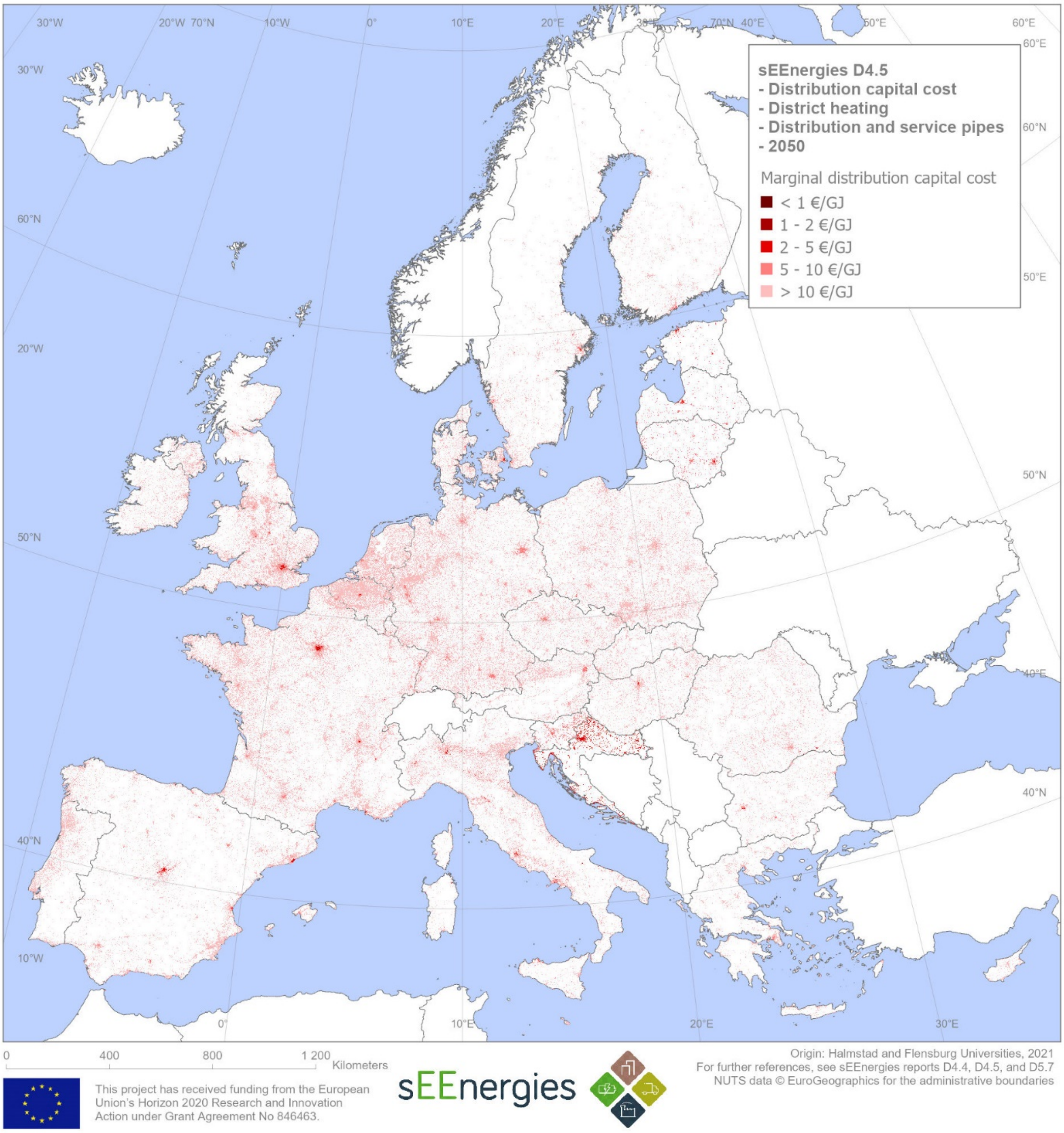

Figure 8. sEEnergies D4.5 overview map: Marginal distribution capital costs for the EU27 Member States plus United Kingdom in 2050, by hectare level including costs for both distribution and service pipes.

As customary, the resulting investment costs are presented in the form of cost curves which, by accumulation of all the studied heat demands (in residential and service sectors for space heating and hot water preparation) possible to supply at each marginal distribution capital cost level, outline corresponding cost levels as function of total heat markets. As indicated above, such heat markets may be national (Member State level), regional (NUTS3 region level), or local/urban (in the context of this report represented by the prospective supply districts). Figure 9 shows the resulting marginal and average cost curves for the entire EU (EU27 plus United Kingdom) for 2030 (left) and 2050 (right) according to this mode of presentation.

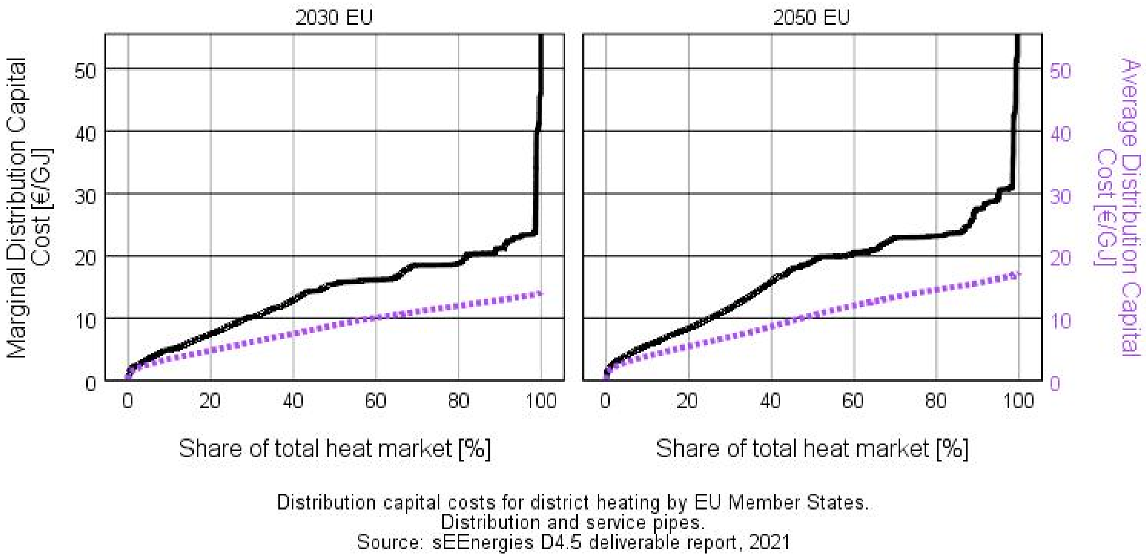

Figure 9. Marginal and average distribution capital cost levels and the corresponding district heat market shares in the EU (27 Member States plus United Kingdom): 2030 (left) and 2050 (right). Cost levels reflect costs for both distribution and service pipes.

Any reader who is familiar with previous studies where the distribution capital cost model was used, and especially so referring to the current year (2015) results from the Heat Roadmap Europe project (see sEEnergies deliverable report D4.4 and references (Urban Persson, Möller, & Wiechers, 2017; Urban Persson et al., 2019), will note here that the cost levels in Figure 9 are of another order of magnitude by direct comparison. For example, current year marginal capital cost levels for a 50% EU28 heat market share were reported at 6.3 euro per Gigajoule, with average costs approximately at three euro per Gigajoule (ibid.), which is significantly lower than these anticipated cost levels for 2030 and 2050.

However, it is important here to emphasize once more that these new results include the costs for both distribution and service pipes, whereas previous accounts have only considered the cost for distribution pipes. In fact, a model validation test run utilising 2015 input data (plot ratio and heat demand density) and where each cost category (distribution and service, respectively) was made explicit, revealed for a corresponding 50% EU28 heat market share a total marginal cost at approximately 11.1 euro per Gigajoule, which in turn was the sum of a distribution pipe term of 6.4 euro per Gigajoule and a service pipe term of 4.7 euro per Gigajoule. Now, in the future case of 2030, as depicted in Figure 9 at left for EU and in Figure 10 for each Member State independently, a 50% EU27 plus United Kingdom heat market share is expected to be found at 15.5 euro per Gigajoule, with marginal cost terms for distribution and service pipes respectively of 8.4 and 7.1 euro per Gigajoule.

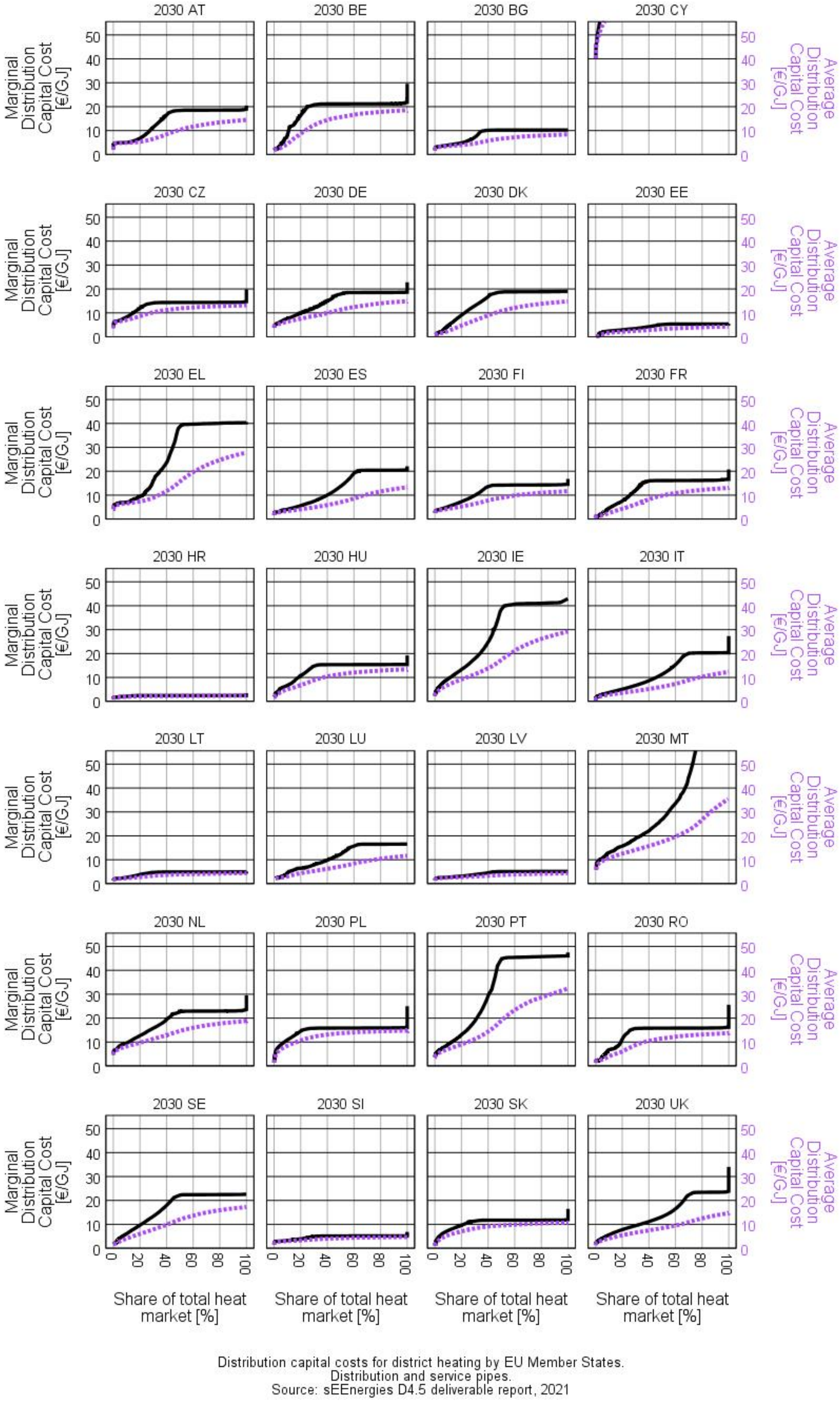

Figure 10. Marginal and average distribution capital cost levels and the corresponding district heat market shares in the 27 EU Member States plus United Kingdom for the year 2030. Cost levels reflect costs for both distribution and service pipes.

From the Member State-level cost curves for 2030 presented in Figure 10 it is observable that the use if nation-specific construction cost levels have an important influence on the results. This represents a model improvement, although unique national cost levels were not possible to derive for all the 28 countries (see further Table 2). Despite this relative shortcoming, which in the future could be remedied by the requestion of national construction cost parameters for all studied countries, the model projects investment costs which no longer simply reflect an average setting applied uniformly.

It is further observable in Figure 10 that a flattening effect appears in the marginal cost curves for several Member States. In this case, the effects of stepwise cost curves are the result of non-continuous cost increments caused by the integer population grid, as describe in section 2.1 above. In short, this means that if population per hectare grows from 1 to 2, the resulting heat demand is doubled, and the distribution capital costs also make a jump. The higher the population density, the smaller is the effect of the increment of 1 per hectare.

Another important observation, illustrated in Figure 11 for the city of Vienna, is that conditions in 2030 generally appear to be more similar to those current than to those projected for 2050, where investment cost are expected to have increased further. There seems to be a "window of opportunity" for investments in district heating in the coming ten years, a window which may be closing by 2050.

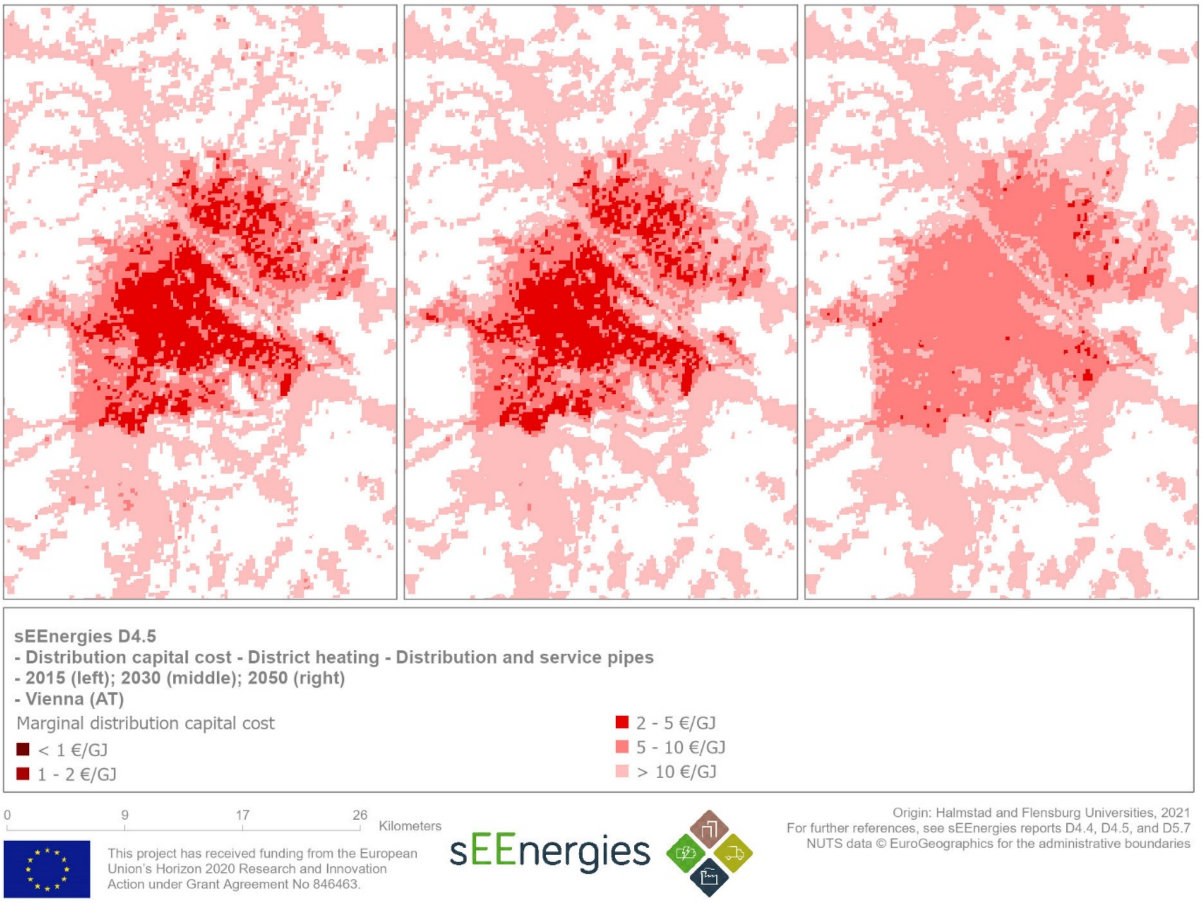

Figure 11. sEEnergies D4.5 detail map: Marginal distribution capital costs for the city of Vienna (AT) in 2015 (left), 2030 (middle), and 2050 (right), by hectare level including costs for both distribution and service pipes.

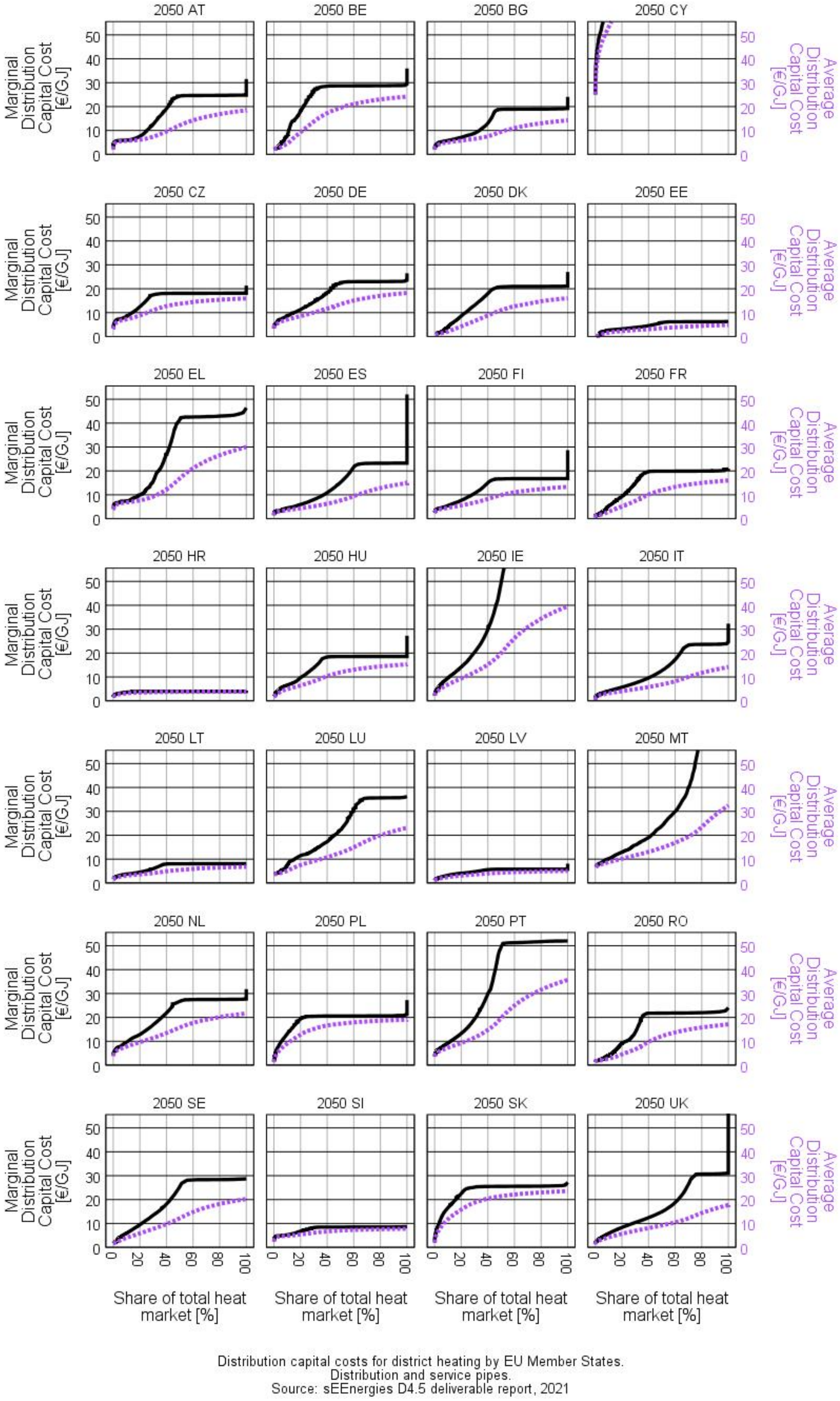

Figure 12. Marginal and average distribution capital cost levels and the corresponding district heat market shares in the 27 EU Member States plus United Kingdom for the year 2050. Cost levels reflect costs for both distribution and service pipes.

As outlined in Figure 9 at right and in Figure 12 independently for each country, for the far future case of 2050, investment costs for district heating have increased in general compared to 2030 levels. In absolute numbers, a 50% EU27 plus United Kingdom heat market share is expected to be found at approximately 19.2 euro per Gigajoule, with marginal cost terms for distribution and service pipes respectively of 9.9 and 9.3 euro per Gigajoule (average investment costs at this heat market share for anticipated at some ten euro per Gigajoule). In relative terms, if considering total marginal cost levels, this increase is in the order of 24% relative 2030 (+73% relative 2015 test case reference). If considering the two underlying cost categories, the increase for investments in distribution pipes is in the order of 18% relative 2030 (+54% relative 2015 test reference), and for service pipes in the order of 31% relative 2030 (+100% relative 2015 test reference).

Due to a wide range of local variations, however, these EU-level results are not necessarily representative of unique local conditions and circumstances found throughout the continent but represent aggregated average values for the total study population. One example of local conditions deviant from the overall EU average trend may be seen in the Swedish city of Malmö (3rd largest city in Sweden), as depicted in Figure 13 for 2015 (model test reference case, left), 2030 (middle), and for 2050 (right). Here, likely due to continued high concentrations of inner-city heat demand densities, few future changes are expected which is observable in a principally maintained spatial distribution.

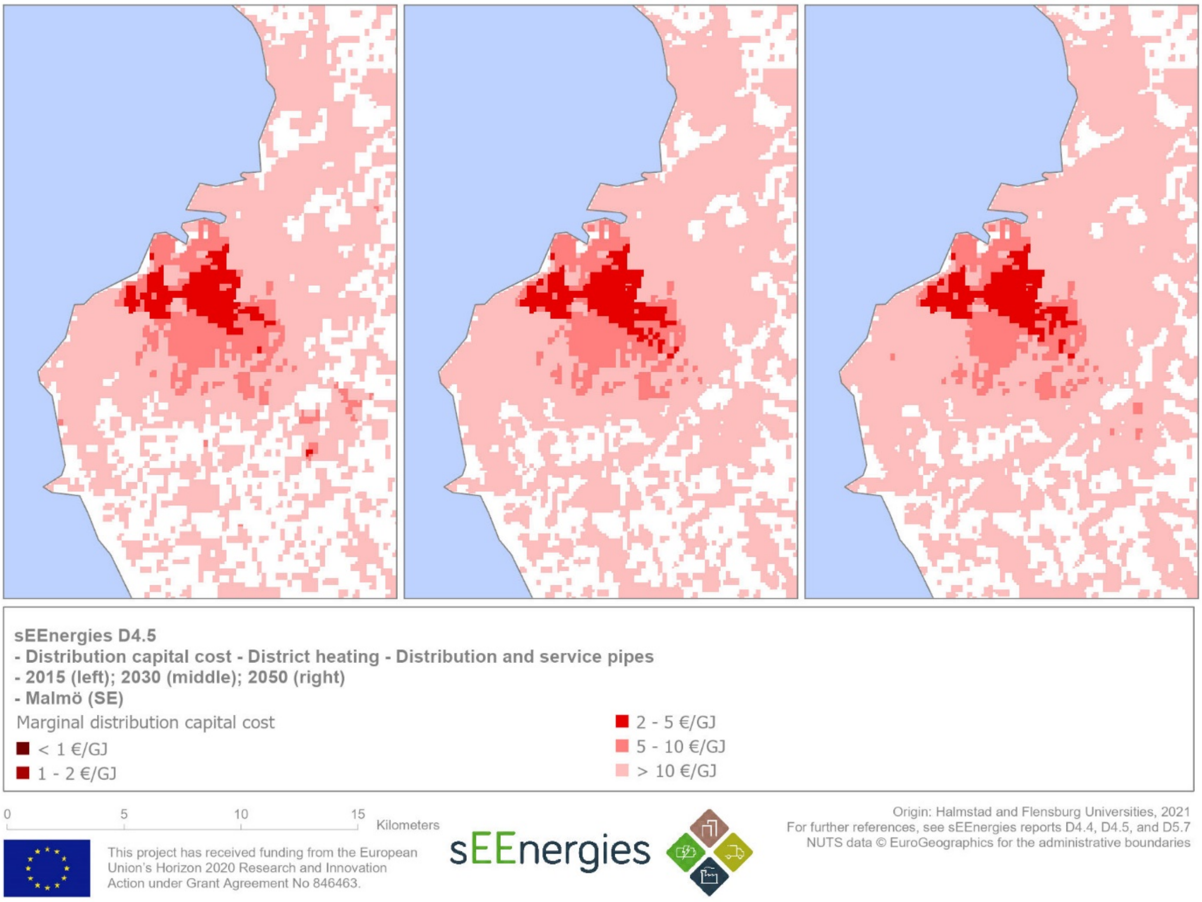

Figure 13. sEEnergies D4.5 detail map: Marginal distribution capital costs for the city of Malmö (SE) in 2015 (left), 2030 (middle), and 2050 (right), by hectare level including costs for both distribution and service pipes.

Another case study example is that of the city of Dublin in Ireland, which is presented in Figure 14. Here, current year investment costs levels are changing already up to year 2030 but maintains on the other hand some quite beneficial conditions for cost-effective investments up to the far future year of 2050.The drivers behind this, and a multitude of other unique local conditions, is very difficult to pinpoint exactly, since, as this study has shown, several underlying factor influence the conditions for feasible network heat distribution.

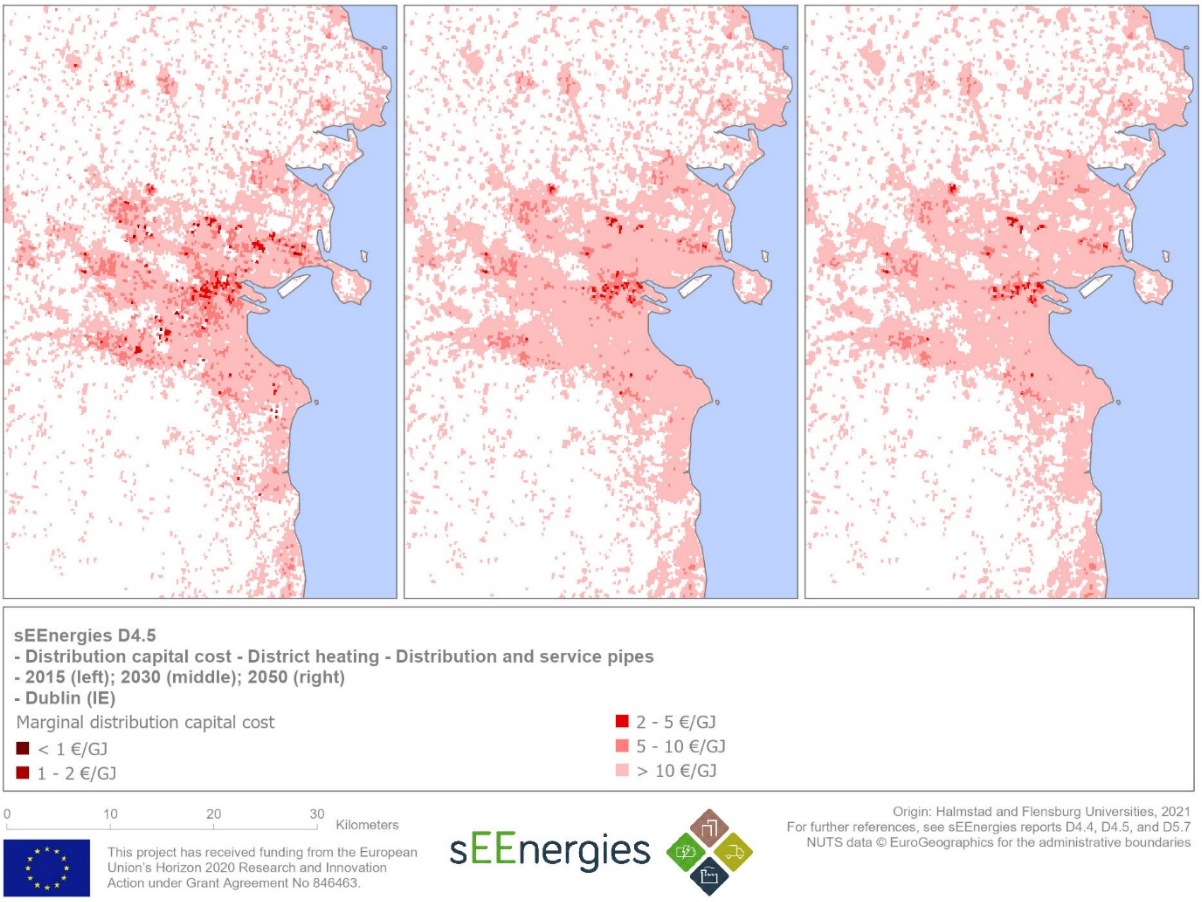

Figure 14. sEEnergies D4.5 detail map: Marginal distribution capital costs for the city of Dublin (IE) in 2015 (left), 2030 (middle), and 2050 (right), by hectare level including costs for both distribution and service pipes.

First and foremost, the "physical suitability" for district heating, i.e. the heat demand density itself, is recognised as a key driver: without sufficiently high building heat demands to provide, be it volumetrically obtained by high specific heat use in buildings (heat use per floor area) or by high spatial concentration of buildings (floor areas by land area), energy lean or not, there is of course no opportunity for cost-effective heat distribution at all. The question in this respect then becomes at what levels of heat demand density that such feasible conditions appear? Well, this question could be answered with reference to heat demand classification (see further section 4 below), or other possible distinctions, but will eventually be the decision, the prioritisation, the preference, and the strategy, of the investor.

Secondly, as we have seen, two counteracting trends anticipated to prevail in the coming years, that of continued energy savings in buildings (retrofits, refurbishments etc.) and that of urbanisation and population growth, play out against each other to the effect that physical suitability in some cases remain quite unchanged, and that in other instances, the one or the other become dominating leading to decreasing and increasing heat demands respectively. For the particular case of large-scale district heating systems, however (city-wide systems), which correctly may be understood as dedicated urban infrastructures, the larger metropolitan areas of Europe are expected to provide also in the coming years sufficient concentrations of heat demands to allow feasible heat distribution. This is exemplified for the case of the French capital Paris in the D4.5 Datasets Web-App screenshot depicted in Figure 15. According to our findings, district heating pipes, including both distribution and service pipes, should be possible to deploy in the inner-city areas of this great city at or below marginal cost levels of two euro per Gigajoule in 2030.

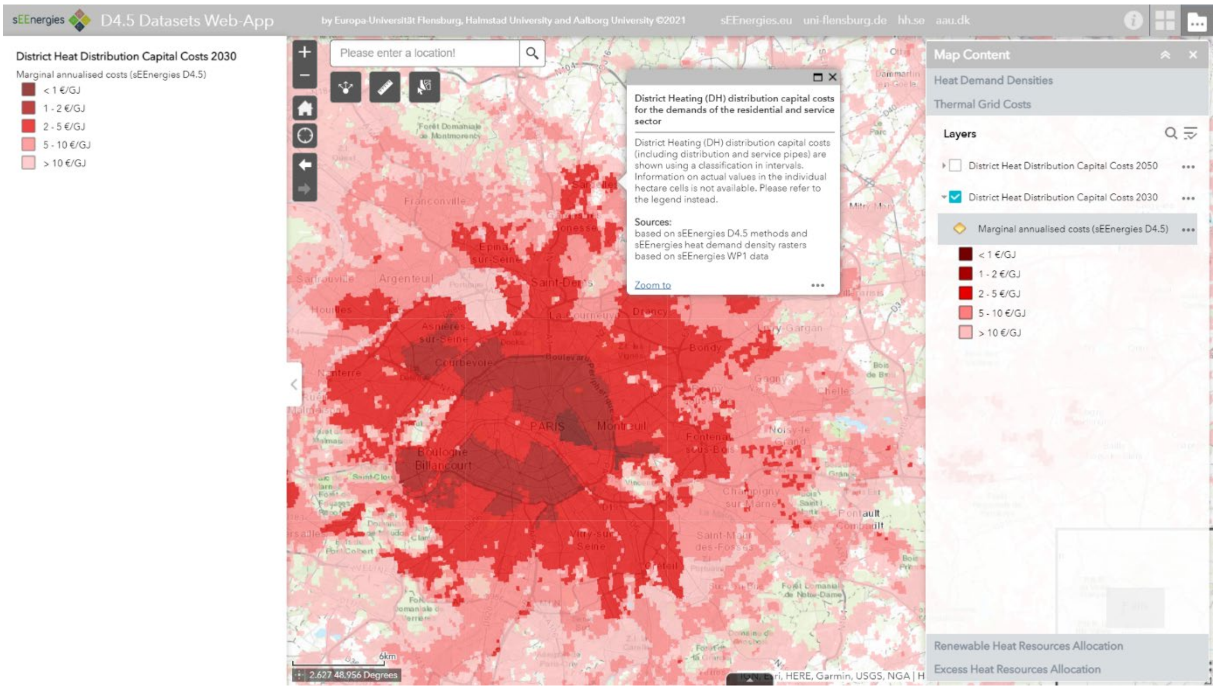

Figure 15. Screenshot from the D4.5 Datasets Web-App with active operational layer: District heat distribution capital costs in 2030 for the Paris region in France.

Thirdly, many additional drivers influence the future of district heating and other heat supply alternatives in Europe, the nature of which may be e.g. technical, economic, organisational, and political. It is vital to keep in mind that, as far as the heat sector and the built environment is concerned, the local perspective represent another important driver, or context, by which to determine the most cost-effective solutions and technologies for us to obtain increased energy efficiency.

In this sense, the systemic perspective may be said to be yet another driver for the future of district heating systems in Europe, because it is only by such perspectives that the synergetic benefits of exploiting locally available heat resources, such as for example industrial and energy sector excess heat as well as renewables in the form of biomass, solar, and geothermal, are possible to conceive and obtain. The final exercise of this work, described in section 4 below, consists in performing an assessment and allocation of such local resources available in 2030 and 2050.

4 Allocation of local resources for 2030 and 2050

In order to establish a geospatial relationship between sinks and sources, local heat sources and locally available resources are to be allocated to prospective supply districts and their heat demand. The allocation is a one-directional matching between modelled future heat demand within delineated areas, which could comprise future district heating areas, and the presence of heat sources. Economic considerations of accessibility, logistics, and technologies required are not included. Limitations of the quantities, seasonal variations, and their dispatch are not considered, as they will be identified on national levels by the energy systems modelling in WP6. The result of the allocation is therefore a specification of the geographically determined availability of heat sources on the local level.

Low-grade or low-enthalpy heat sources may cover a significant fraction of the heat demand. Sources and their potential sinks depend on local geography. Excess heat from industry and the energy sector as well as from wastewater treatment plants, point sources exemplified for northern Italy in Figure 16, are allocated to Prospective Supply Districts (PSD). In the analysis driven by the proximity between excess heat sources and heat sinks, heat sources are assigned to the nearest existing or potential heating network, assuming that geographical proximity is related to economic feasibility (see next subsection). Furthermore, using a capacitated network analysis algorithm described in (Möller et al., 2019), sources from industry are allocated to PSD that can match their capacities, in order to avoid excess heat ratios (U. Persson, Möller, & Werner, 2014) much greater than 1.

Besides quantifiable point locations of excess heat supply, those sources that are geographically distributed are allocated based on local availability. Renewable heat sources like deep geothermal heat, solar radiation and residual biomass potentials have been assigned to PSD using a classification of their intensity or availability. Other potential low-grade heat sources, such as rivers, lakes, and other ambient heat sources for heat pumps; large building compounds with air-conditioning; metro stations or the like have not been considered at this point.

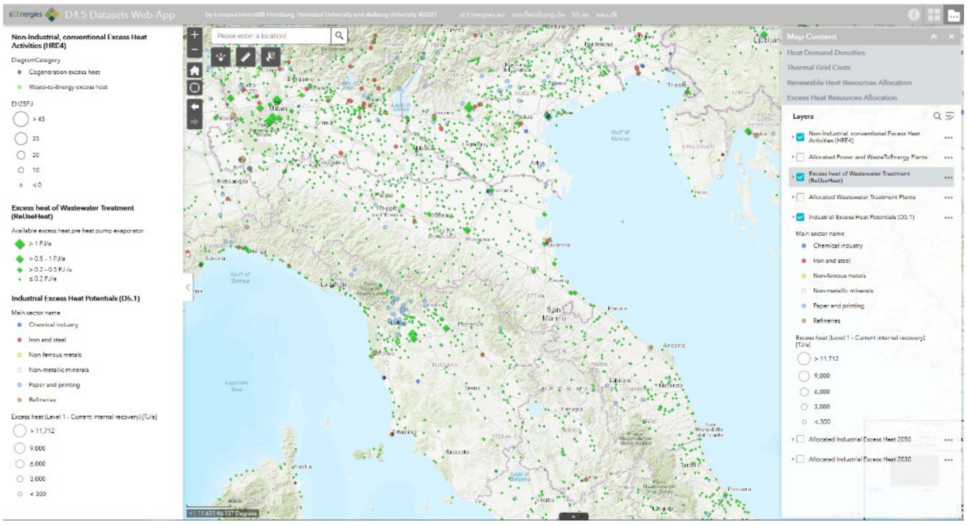

Figure 16. Screenshot from the D4.5 Datasets Web-App with active operational layers: Non-industrial, conventional excess heat activities (from Heat Roadmap Europe 4 project), excess heat from wastewater treatment plants (from ReUseHeat project), and industrial excess heat potentials (sEEnergies project), for the area of northern Italy.

4.1 Definition of (future) Prospective Supply Districts

A Prospective Supply District (PSD) comprises the largest possible geographical extent of a potential district heating system. It could be understood as a zoning map. PSD are generated for the year 2050 using the maximum heat demand density between the years 2015, 2030 and 2050, so they include the maximum extent of supply areas in the time horizon of the project (2015-2050). As future urban areas will have a greater geographical extent, the shape and geographical properties of future PSD are associated to present PSD. A unique ID for future PSDs is added, as visible in the D4.5 Datasets Web-App screenshot for the Amsterdam region in the Netherlands in Figure 17.

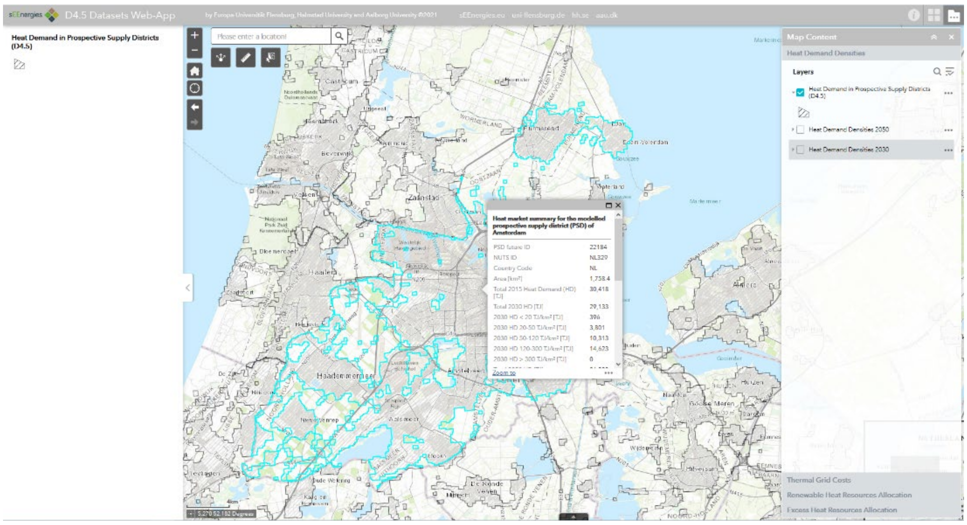

Figure 17. Screenshot from the D4.5 Datasets Web-App with active operational layer: Heat demand in prospective supply districts in 2030 and 2050 by heat demand density classes for the Amsterdam region in the Netherlands.

For each PSD, the summation of heat demands by density class, see Table 3, allows for a rough estimate of the district heating potential, following a classification by the Danish Energy Agency and (Energistyrelsen, 2012) adopted by the Heat Roadmap Europe project. In a first iteration, the share of district heating is calculated for each PSD based on a physical assessment by heat demand density. Heat demands are summarized by density class (< 50, 50-120, 120-300, > 300 TJ/km²) for each PSD. The result is a numerical dataset, which describes potential local heat markets. Heat demands in rural areas outside PSD are generally assumed to be irrelevant for district heating.

Table 3. Nominal and mapped heat demand density classes with interpretations regarding corresponding district heating system generations

Nominal density class	Mapped density class	Interpretation
20 –50 TJ / km²	200 –500 GJ / ha	Potential for 4th generation district heating
50 –120 TJ /km²	500 – 1,200 GJ/ha	Current 3rd generation district heating in countries with active policies
120 –300 TJ / km²	1,200-3,000 GJ/ha	Current 3rd generation district heating is possible
> 300 TJ / km²	> 3,000 GJ/ha	District heating is possible

4.2 Allocation of local excess heat resources

Excess heat sources are allocated to future heat demands after georeferencing sources and identifying spatially concentrated heat demands in prospective supply districts (PSDs). For point-located resources, all non-industrial excess heat activities are allocated to the nearest PSD by means of simple (crow-flight) proximity. A 30km threshold was applied for power and Waste-To-Energy plants (from the Heat Roadmap Europe 4 project, see further (Urban Persson et al., 2017)), but for wastewater treatment plants (from the ReUseHeat project, see further (Urban Persson & Averfalk, 2018)) a maximum distance of 10km distance was applied.

Excess heat potentials of industrial sites (from the sEEnergies project, see further (Fleiter, Manz, et al., 2020)) are distributed to the PSDs within a maximum distance via the major road network of 30km using a capacitated network allocation and a simplified approach to comprise annual heat demand.

- For 2030, the allocation used excess heat potentials estimated to be the maximum waste heat attainable, if an exhaust gas is cooled to 55°C. This can potentially be used directly in 4th Generation district heating grids that work on a lower temperature. Besides, for 2030 current rates of internal heat recovery level is assumed. (-> "Level2")
- For 2050, the allocation used excess heat potentials estimated to be the maximum waste heat attainable if an exhaust gas is cooled to ambient temperatures. This can potentially be used as a heat source for large scale heat pumps feeding into 3rd or 4th generation district heating grids. Besides, for 2050 the full rate of internal heat recovery of excess heat at the industrial sites is assumed. (-> "Level1_r")
- For more detailed information please refer to the sEEnergies D5.1 report: (Fleiter, Manz, et al., 2020; Fleiter, Neuwirth, et al., 2020).

The allocation results in a binary code (true/false) for each PSD, which states whether excess heat is available. For each PSD, excess heat sources are allocated by using the method explained above and a database table attributes the excess heat potential allocated to it, as illustrated in the screenshot presented in Figure 18.

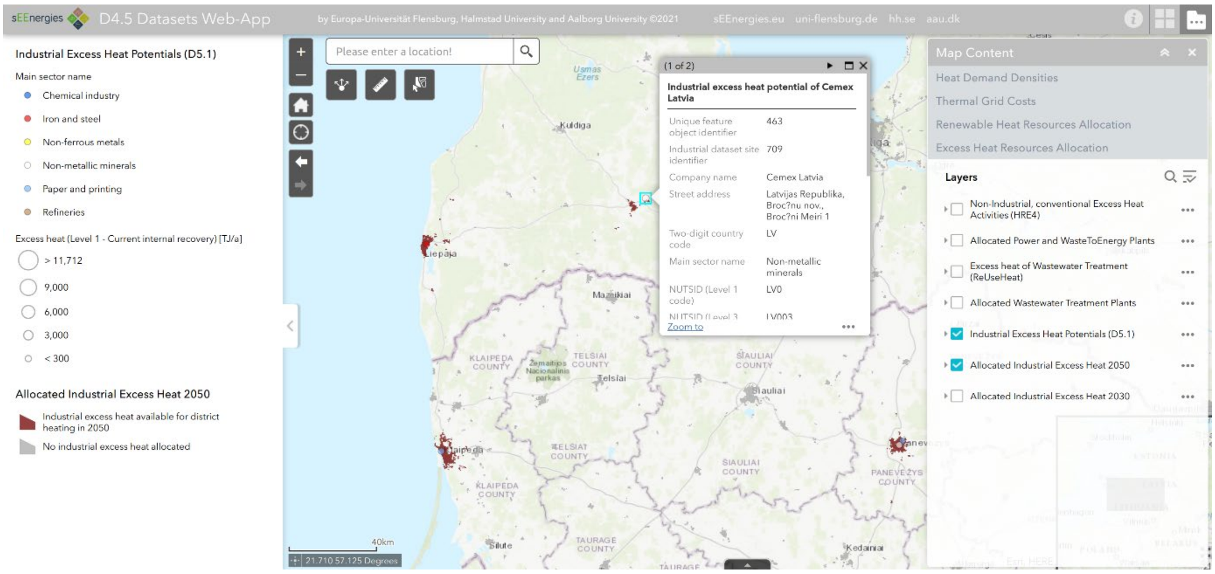

Figure 18. Screenshot from the D4.5 Datasets Web-App showing industrial excess heat potentials mapped and allocated to individual PSDs.

4.3 Allocation of local renewable heat resources

The availability of renewable heat sources in the PSD is classified as described in the following. The solar thermal potential is being assessed and classified by the annual solar radiation at optimal angle (based on PVGIS data (Huld, Müller, & Gambardella, 2012)) and summarised within each PSD, as outlined in the screenshot example for the area of north-western France in Figure 19.

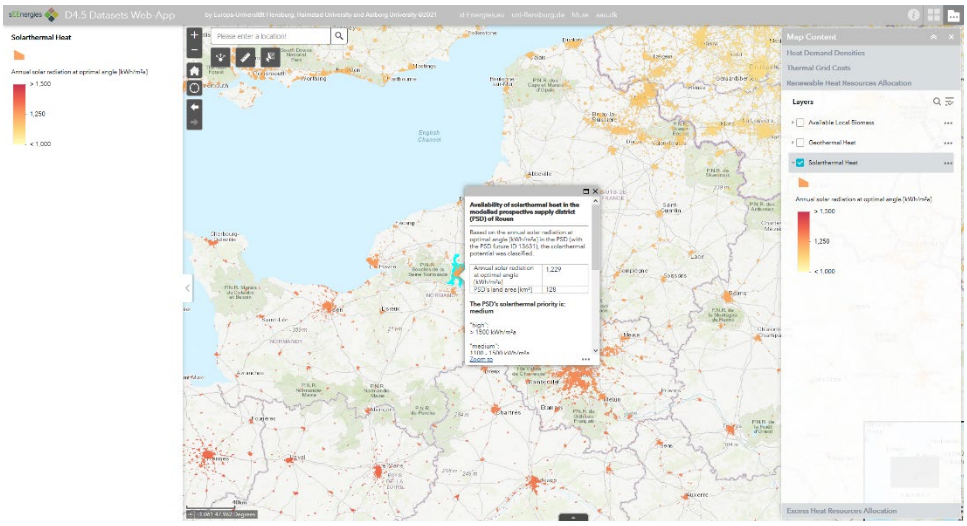

Figure 19. Screenshot from the D4.5 Datasets Web-App with active operational layer: Solar thermal heat for the area of north-western France.

The available residual biomass from forestry and agriculture is mapped by spatial disaggregation and association to the nearest neighbourhood of PSDs. In the cases of solar thermal and biomass energy, potentials and capacities are further to be determined by overall considerations in the upcoming energy systems analysis in WP6, which will make final decisions on alternative and competing heat supply opportunities.

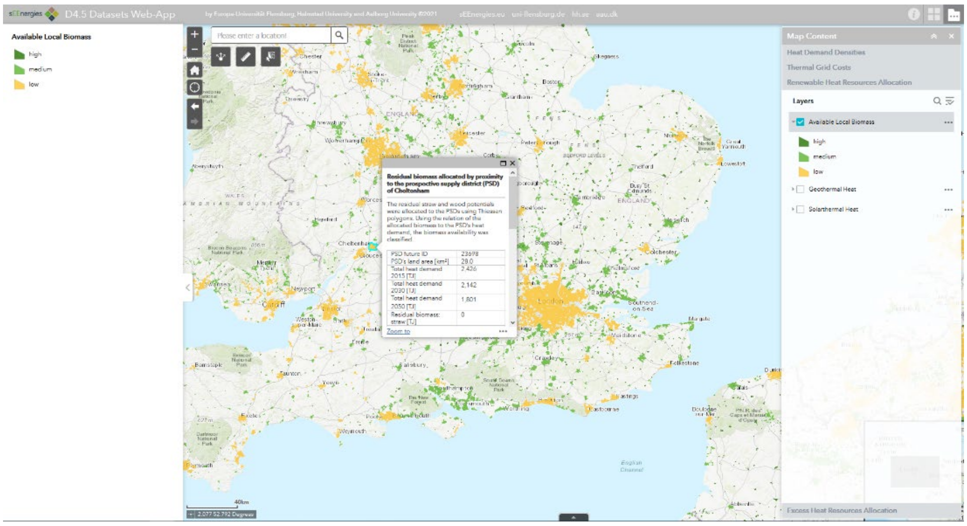

Figure 20. Screenshot from the D4.5 Datasets Web-App with active operational layer: Available local biomass for the south-eastern region in the United Kingdom.

Residual biomass (straw and wood) resources (from the BioBoost project, see further (Pudelko, Borzecka-Walker, & Faber, 2013)) are first spatially disaggregated to the 1-hectare level using Corine Land Cover data (European Environment Agency, 2018) and then assigned to each PSD using Thiessen polygons. The resulting biomass availability is therefore a quantification of what may be available from the immediate neighbourhood of a potential district heating scheme, without any biomass trade or logistics being considered at this point. The classification of available biomass is based on the relation between the available biomass and the 2015 demand of the PSD (see Figure 20 with a screenshot of biomass availabilities in the south-eastern region in the United Kingdom).

For deep geothermal resources, finally, the location of a PSD near to an area of geothermal heat potential is attributed in the database. Geothermal heat potentials across Europe have been mapped in the GeoDH project (Dumas & Bartosik, 2014; GeoDH, 2017). Suitable reservoirs, aquifers and basins have been charted along with minimum heat flow densities and temperature gradients. A simple interpretation identifies suitability based on basin characteristics and temperature gradients, as described in Table 4.

Table 4. Deep geothermal heat priorities

"Priority"	high	medium	low
Temperature at 2000m depth greater than 90 deg. C	X		
Temperature at 1000m depth greater than 50 deg. C		X	
Other hot reservoir		X	X
Neogene basins	X		
Hot sediment aquifer	X		
Heat flow density greater than 90 mW/m²	X		

For each PSD, the characteristics of nearby geothermal regions (less than 10km away from the PSD boundaries) have been associated to the dataset that describes the PSDs' renewable heat potentials, which is exemplified for the urban area of Berlin in Germany in Figure 21. Based on the presence and absence of the listed geological phenomena close to the PSDs, the geothermal potential was estimated by priority, as outlined in Table 4. Other combinations than the displayed ones are interpreted as no potential (non-existent) according to the used data.

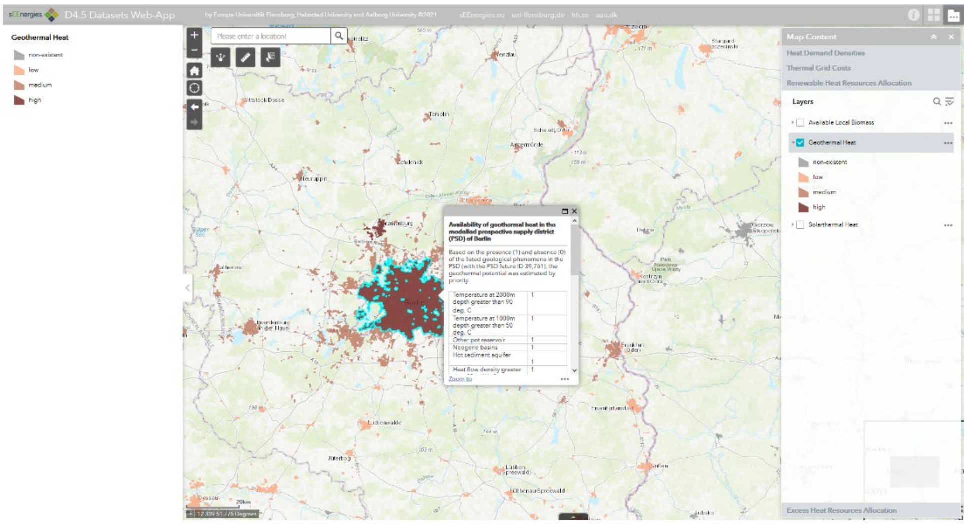

Figure 21. Screenshot from the D4.5 Datasets Web-App with active operational layer: Geothermal heat for the city of Berlin with surrounding areas in Germany.

The account given in this report regarding the allocation of local resources for 2030 and 2050 is introductory and will be extended in depth and detail in the final WP5 report in the sEEnergies project (D5.7: Spatial models and spatial analytics results). Some of the mentioned approaches are still under development and updates are to be expected during the remainder of the project. At the time of writing, the results from this allocation may be viewed at the D4.5 Datasets Web-App, but the resulting datasets are not available for public download.

5 Conclusions

This report has presented key methodological aspects and results from the work within the sEEnergies project to develop approaches and models by which to assess district heating investment costs and allocation of local resources for EU28 in 2030 and 2050. The results are presented here in the form of map images but are also shared at a designated web app (sEEnergies D4.5 Datasets Web-App) as operational layers, as well as in the form of tabular numerical datasets in which national, regional, and urban level aggregations are included.

The report represents the second of three separate accounts by which the sEEnergies work on representative thermal grids is to be documented. The parallel D4.4 report (Cost and capacity analysis for representative EU energy grids depending on decarbonisation scenarios) and the upcoming D5.7 report (Spatial models and spatial analytics results, due in project month 30, i.e. February 2022) represents the other two accounts. While both D4.4 and D4.5 touch upon key approaches and findings from this work, the full description of methods and results will be presented in D5.7.

Although several new methodological elements are introduced, the biggest challenge in the presented work has consisted in the anticipation of the spatial distribution of future building heat demands on hectare level, here assessed for the two study years of 2030 and 2050. During previous project collaborations, for example in the Heat Roadmap Europe project series, the authors have contributed to the general development of mapping approaches by which to assess such spatial distributions under current year settings, which permits of another level of certainty since input data can be established on the basis of actual empirical evidence, such as energy statistics, satellite imagery, population censuses etc. While a driver during such earlier projects has been the obtaining of higher levels of resolution in the modelling, typically moving from regional, to square kilometre, eventually to hectare level analyses, the key driver here has been to find a suitable balance between the inherent complexity associated to any kind of future assessment and the relative simplicity needed to build manageable and functionable spatial models.

Regarding the assessed specific investment costs for future district heating systems, a conservative attitude has been maintained in the establishment of effective width and construction cost parameter values (both intrinsic underlying phenomena influencing the final costs), rather to overestimate than to underestimate future cost levels. Notably, moreover, this work presents, for the first time as an output from the distribution capita cost model, investment costs which include both distribution and service pipes.

Total marginal capital cost levels, thus representing investments both in distribution and service pipes, increase from a test reference case resembling the current year (2015) by approximately 40% by 2030 (from some 11.1 to 15.5 euro per Gigajoule) and by roughly 73% by 2050 (from 11.1 to 19.2 euro per Gigajoule). This general circumstance suggests a “window of opportunity” for investments in district heating system in the EU in the coming 10-year period, a window which appears to begin closing during the years leading up to 2015.

However, local variations seem to be a trademark characteristic also of future heat demand densities, why the local perspective remains the main entrance into the domain of synergetic and cost-effective exploitation and recovery of societal heat residuals and renewable heat resources such as solar, biomass, and deep geothermal assets. For the allocation of such local resources for 2030 and 2050 in the context of this work, we have utilised results and data from several other European projects, such as the Heat Roadmap Europe project, the BioBoost project, the GeoDH project, and several other geodata information sources. The spatial targets for the allocation of local resources here are the Prospective Supply Districts (PSD), which may be described as coherent urban areas with heat demand densities above the threshold 20 Terajoules per square kilometre. The allocation results, as well as the resulting district heating investment costs, are presented as operational web map layers at a new web map app, the sEEnergies D4.5 Datasets Web-App.

Although the general trend indicates relatively higher cost levels for district heating in the coming years, rich opportunities for network heat distribution are expected to prevail in highly dense inner-city districts, and especially so in larger coherent metropolitan areas. Two counteracting main trends, that of urbanisation and population growth on one hand, and that of energy saving measures in buildings on the other, result in some cases in a remarkable status quo with respect to heat demand densities in the modelled future year settings. In some cases, where the former gains the overhand, heat densities continue to increase with the consequence of lower investment costs for district heating systems. In other cases, where the latter dominates over the former, actual heat demands are decreasing with higher investment costs as an unavoidable consequence.

What will be the future case in your particular city? A hint may be that modelling assumption we have adhered to throughout this exercise, namely that where populations have increased historically (well, from the 1990s and onwards at least), there they will continue to grow. Where they have decreased, the decline will continue.

6 Appendix / Datasets / Map Layers

6.1 D4.5 Datasets

- Numerical datasets with accumulated marginal and average district heat capital cost curves at national and regional level for 2030 and 2050 (.csv files).
- Allocated local resources at urban level (Prospective Supply Districts) for 2030 and 2050 (feature layers)

6.2 D4.5 Geographical layers

Table 5. Overview table of D4.5 geographical layers

Layer *or* **Group**	**Remark / Description**
Heat Demand Densities	
Heat Demand Densities 2050	Based on the sEEnergies WP1 data and the D4.5 methods
Heat Demand Densities 2030	As above
Heat Demand in Prospective Supply Districts (PSDs) (D4.5)	Heat demands aggregated by PSD (maximum extent) and heat demand density class
Thermal Grid Costs	
District Heat Distribution Capital Costs 2050	Based on future heat demand densities and D4.5 methods
District Heat Distribution Capital Costs 2030	As above
Renewable Heat Resources Allocation	
Available Local Biomass	
Geothermal Heat	
Solar thermal Heat	
Excess Heat Resources Allocation	
Non-industrial, conventional excess heat activities (HRE4)	Location and theoretical potentials of power and Waste-To-Energy plants
Allocated Power and Waste-To-Energy plants	
Excess Heat of Wastewater Treatment (ReUseHeat)	
Allocated Wastewater Treatment Plants	
Industrial Excess Heat Potentials (D5.1)	
Allocated Industrial Excess Heat 2050	
Allocated Industrial Excess Heat 2030	

7 References

AECOM, ETI, TotalFlow, Engie, University, L., & COWI. (2017). *Reducing the capital cost of district heat network infrastructure*.

Besier, R., Klöpsch, M., & Wagner, A. (2009). *Reicht für Kunststoffmantelrohre die Standarddämmung heute noch aus?*

Bygnings- og Boligregisteret (BBR). (2018). Bygnings- og Boligregisteret (BBR).

Center for International Earth Science Information Network. (2019). *Gridded Population of the World v4*. Retrieved from Columbia University, Accessed December 2020: https://sedac.ciesin.columbia.edu/data/collection/gpw-v4:

Personal communication with Ignacio Cuesta from ADHAC (Asociación de empresas de redes de calor y frío), (2020).

Denarie, A. (2020). Personal communication with Alice Denarie (Politecnico di Milano). In.

Dorotić, H. (2020). Personal communication with Hrvoje Dorotić (Universitetet i Zagreb). In.

Dumas, P., & Bartosik, A. (2014). *GeoDH: Geothermal DH Potential in Europe*. Retrieved from Geo-DH project (Promote Geothermal District Heating Systems in Europe). Intelligent Energy Europe Programme. Available at (2017-08-27): http://geodh.eu/wp-content/uploads/2014/11/GeoDH-Report-D-2.2-final.pdf:

EC. (2016a). *COM(2016) 51 final. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. An EU Strategy on Heating and Cooling. {SWD(2016) 24 final}*. European Commission, Brussels.

EC. (2016b). *EU Reference Scenario 2016 - EU and EU country results (Release date: 2016-12-15)*. Retrieved from Energy modelling - EU Reference Scenario 2016. EU Open Data Portal - Access to European Union open data. Directorate-General for Energy. European Commission. Available at (2020-07-14): https://ec.europa.eu/energy/sites/ener/files/documents/AppendixRefSce.xls:

Edit, N. (2020). Personal communication with Nagy Edit from MaTáSzSz (Magyar Távhőszolgáltatók Szakmai Szövetsége). In.

Energistyrelsen. (2012). *Individual Heating Plants and Energy Transport: Technology Data for Energy Plants, May 2012*. Retrieved from Energistyrelsen (Danish Energy Agency). :

European Environment Agency. (2018). *Copernicus: Corine Land Cover (CLC), Version 2020_20u1*. Retrieved from European Environment Agency (Accessed June 2020): https://land.copernicus.eu/pan-european/corine-land-cover:

Fleiter, T., Manz, P., Neuwirth, M., Mildner, F., Persson, U., Kermeli, K., . . . Rutten, C. (2020). *Documentation on excess heat potentials of industrial sites including open data file with selected potentials (D5.1)*. Retrieved from sEEnergies - Quantification of synergies between Energy Efficiency first principle and renewable energy systems. Available at (2020-06-19): https://doi.org/10.5281/zenodo.3896380. :

Fleiter, T., Neuwirth, M., Mildner, F., Manz, P., Persson, U., Kermeli, K., . . . Rutten, C. (2020). sEEnergies D5.1 Dataset Web-App. In. sEEnergies ArcGIS Online Web-Apps hosted by Europa-Universität Flensburg. Available at (2020-02-24): https://tinyurl.com/sEEnergies-D5-1. .

GeoDH. (2017). GeoGH: Geothermal district heating.

Gurklienė, R. (2020). Personal communication with Ramunė Gurklienė from LŠTA (Lietuvos šilumos tiekėjų asociacija). In.

Huld, T., Müller, R., & Gambardella, A. (2012). A new solar radiation database for estimating PV performance in Europe and Africa. *Solar Energy, 86*(6), 1803-1815. doi:https://doi.org/10.1016/j.solener.2012.03.006

Lund, H., Werner, S., Wiltshire, R., Svendsen, S., Thorsen, J. E., Hvelplund, F., & Mathiesen, B. V. (2014). 4th Generation District Heating (4GDH): Integrating smart thermal grids into future sustainable energy systems. *Energy, 68*(0), 1-11. doi:http://dx.doi.org/10.1016/j.energy.2014.02.089

Lund, H., Østergaard, P. A., Chang, M., Werner, S., Svendsen, S., Sorknæs, P., . . . Möller, B. (2018). The status of 4th generation district heating: Research and results. *Energy, 164*, 147-159. doi:https://doi.org/10.1016/j.energy.2018.08.206

Möller, B., Wiechers, E., Persson, U., Grundahl, L., Lund, R. S., & Mathiesen, B. V. (2019). Heat Roadmap Europe: Towards EU-Wide, local heat supply strategies. *Energy, 177*, 554-564. doi:https://doi.org/10.1016/j.energy.2019.04.098

Persson, U., & Averfalk, H. (2018). *Accessible urban waste heat. Deliverable 1.4*. Retrieved from ReUseHeat. Recovery of Urban Excess Heat:

Persson, U., Möller, B., & Werner, S. (2014). Heat Roadmap Europe: Identifying strategic heat synergy regions. *Energy Policy, 74*(0), 663-681. doi:http://dx.doi.org/10.1016/j.enpol.2014.07.015

Persson, U., Möller, B., & Wiechers, E. (2017). *Methodologies and assumptions used in the mapping. Deliverable 2.3: A final report outlining the methodology and assumptions used in the mapping. August 2017*. Retrieved from Heat Roadmap Europe 2050, A low-carbon heating and cooling strategy. Available at (2018-12-10): (https://heatroadmap.eu/wp-content/uploads/2018/11/D2.3_Revised-version_180928.pdf):

Persson, U., & Werner, S. (2010). Effective width - The relative demand for district heating pipe lengths in city areas. *12th International Symposium on District Heating and Cooling*.

Persson, U., & Werner, S. (2011). Heat distribution and the future competitiveness of district heating. *Applied Energy, 88*, 568-576. doi:10.1016/j.apenergy.2010.09.020

Persson, U., Wiechers, E., Möller, B., & Werner, S. (2019). Heat Roadmap Europe: Heat distribution costs. *Energy, 176*, 604-622. doi:10.1016/j.energy.2019.03.189

Pudelko, R., Borzecka-Walker, M., & Faber, A. (2013). *The feedstock potential assessment for EU-27 + Switzerland in NUTS-3. D1.2_v1.0*. Retrieved from BioBoost: Biomass based energy intermediates boosting biofuel production. Co-funded by the European Commission FP7, Directorate-General for Transport and Energy. Grant No. 282873:

Rasmussen, J., & Hansen, A. B. (2020). Personal communication with Jakob Rasmussen and Anders Bøgelund Hansen (FjernvarmeFyn). In.

Roger, C. (2020). Personal communication with Christophe Roger - ADEME (Agence de la transition écologique). In. Paris, France.

Feasibility study of a district heating system in the Spanish city of Gijón, 114 (2017).

Schepers, B., Naber, N., Wijngaart, R. v. d., Polen, S. v., Molen, F. v. d., Langeveld, T., . . . Beek, M. v. (2019). *Functioneel ontwerp Vesta 4.0*, Delft.

Schiavina, M., Freire, S., & MacManus, K. (2019). *GHS population grid multitemporal (1975, 1990, 2000, 2015) R2019A.* . Retrieved from European Commission, Joint Research Centre (JRC) DOI: under release, updated on: http://ghsl.jrc.ec.europa.eu/documents/GHSL_Data_Package_2019.pdf:

Styrelsen for Dataforsyning og Effektivisering. (2021). Kortforsyning. *Matrikelkortet*.

Svensk Fjärrvärme AB. (2007). *Kulvertkostnadskatalog (The district heating pipe cost report)*, Stockholm.

Werner, S. (2006). *The New European Heating Index*. Paper presented at the 10th International Symposium on District heating and Cooling, Hannover, Germany.

Wiechers, E., Möller, B., Persson, U., & Sánchez-García, L. (2021). sEEnergies D4.5 Datasets Web-App (Future District Heating Map). In. sEEnergies ArcGIS Online Webmapping Application managed by Europa-Universität Flensburg. Available at (2021-03-11): https://euf.maps.arcgis.com/apps/webappviewer/index.html?id=417665ed989a4319acfbec2b92a08332.