sEEnergies

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

D5.7

Spatial models and spatial analytics results

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Executive Summary

The present report accounts for the spatial models of energy efficiency and the geospatial analysis carried out to quantify and locate energy efficiency potentials across sectors. In the building sector, future heat demands on national scales are being distributed using the age class of built-up areas and innovative models of future population distribution. District heat distribution capital costs combined with heat demand densities allow for the assessment of economic potentials of future district heating. Efficiency potentials in the transport and industrial sectors have been associated to locations, and transmission infrastructures have been mapped. Combining all these aspects, spatial analytics help understanding the opportunities and constraints that arise from the geography of energy systems. Energy efficiency in the three sectors has been mapped at different scales. Cost curves for district heating have been prepared for member states. For use in energy systems analysis, a matrix has been developed that relates energy efficiency in buildings and district heating potentials. Areas of interest for the conversion of natural gas to district heating have been mapped, combining present gas use with infrastructural aspects. Local potentials of district heating have been quantified for almost 150,000 settlements, and potential heat sources from industrial and wastewater treatment plants as well as locally available renewable energy sources have been allocated to potential district heating areas. Finally, to visualise and compare energy efficiency across sectors, technologies, and countries, the sEEnergies Index shows local potentials for improving energy efficiency and utilising synergies in all settlements of the EU27 plus the UK. In conclusion, the report documents how dissemination can be facilitated using the online geospatial information and mapping applications prepared in the sEEnergies Project.

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Acronyms & Abbreviations

Term	Description
BAT	Best available technology
BL	Baseline
DH	District heating
DH-A	Actual District Heating areas
DH-E	Expected District Heating areas
DHDCC	District Heating Distribution Capital Cost (model)
e	Plot Ratio (pr) a.k.a. Building Density [-]
EEP	Energy Efficiency Potential
FE	Frozen Efficiency
GIS	Geographical Information Systems
GJ	Gigajoule
HD	Heat Demand
HDD	Heat Demand Density
HRE4	Heat Roadmap Europe 4
HUDHC	Halmstad University District Heating and Cooling database
kJ	Kilojoule
MWh	Megawatt hour
NUTS	Nomenclature of Territorial Units for Statistics
Peta	Pan-European Thermal Atlas
PSD	Prospective Supply District
UA	Urban Areas
UMZ	Urban Morphological Zones
w	Effective Width [m]
WP	Work package
WWTP	Waste-Water Treatment Plant
WP	Work package

1. Introduction

The present report is the last and final written output from work package 5 (WP5[1]) in the sEEnergies project. In this report, the main focus is directed towards, on the one hand, the spatial models developed to describe European Union (EU) energy efficiency potentials and, on the other hand, the spatial analytics that have been performed to quantify and locate sectoral energy efficiencies and their potential synergies. The overarching ambition with this report is to present our main achievements, approaches, findings, and outputs, by alignment under these two focus areas.

To provide overview and context we would like initially to mention that, during the course of the sEEnergies project (from September 2019 to June 2022), WP5 has functioned as an important internal project vehicle for information and data sharing. Input data on current and future energy characteristics in several energy use sectors were elaborated and prepared in other work packages (WP1: Buildings, WP2: Transport, WP3: Industry, and WP4: Energy grids). They have been integrated into the spatial models developed in WP5 and, in turn, have provided the key underlying information-basis for the spatial analytics. Results from these have been made available to energy systems analysis in WP6, and provided input for external project communication.

The sharing of geospatial data and information, notably with the online web mapping application *The Pan-European Thermal Atlas* (Peta 5.2, 2022) and by means of an associated open data sharing platform *The sEEnergies Open Data Hub* (sEEnergies Open Data Hub, 2020), is part of the originally planned project outcomes. In addition, so-called Story Maps (an online-based interactive form of story-telling utilising narrative text in combination with maps, graphs, photographs etc.), have been prepared for each sector in order to improve the dissemination of project results (sEEnergies mapping team, 2022).

Altogether, in terms of formal project outcomes, WP5 will have produced five public deliverable outputs by the end of the project, as detailed in the following lists[2], where the first three deliverable outputs were finalised prior to the present report:

- *D5.1: Documentation on excess heat potentials of industrial sites including open data file with selected potentials*
    - Internal compilation of data and information on excess heat potentials from industry activities in the 28 EU countries
    - February 2020
    - References: (Fleiter et al., 2020; Manz et al., 2021).

- *D5.2: Documentation and dataset from the analysis and mapping of cities with similar topography and demography and the relation to energy efficient transport and mobility*
    - Internal compilation of data and information from the analysis and mapping of cities with similar topography and demography and the relation to energy efficient transport and mobility
    - February 2020
    - References: (Wiechers, Möller, & Persson, 2020).

[1] WP5 title: Spatial analyses of energy efficiency potentials and development of GIS visualization platform.
[2] The bullet points represent in descending order: Deliverable title, description, due date (month, year), and related references where relevant.

- *D5.3: Online web map application and 1st set of map layers (current year scenario)*
    - First publication of the online visualization tool, with the first set of map layers representing the current year scenario
    - November 2020
    - References: (Möller, Wiechers, Persson, Nielsen, & Moreno, 2020).

In addition to these first three dedicated WP5 outcomes, two related deliverable outputs from work package 4 (WP4[3]) – in which WP5 partner activities on thermal grids modelling, allocation of heat resources, as well as of future year population mapping, were initially conceived and initiated – need to be mentioned here and included in the context of the present report:

- *D4.4: Final cost and capacity analysis for the representative energy grids as function of the decarbonisation scenarios version*
    - Report describing the data and information gathered on the state of the art of existing European energy grids as well as the total costs for the representative energy grids when designing an efficient and decarbonized energy system
    - February 2021
    - References: (Meunier, Protopapadaki, Baetens, & Saelens, 2021; Meunier, Protopapadaki, Persson, et al., 2021; Persson, Möller, & Wiechers, 2017; Urban Persson & Sven Werner, 2010; Persson & Werner, 2011).

- *D4.5: District heating investment costs and allocation of local resources for EU28 in 2030 and 2050*
    - Report on the investment costs and allocation of resources to achieve Energy efficiency scenarios in 2030 and 2050
    - February 2021
    - References: (Möller, Wiechers, Persson, Grundahl, & Connolly, 2018; Möller et al., 2019; Persson, Möller, Sánchez-García, & Wiechers, 2021; Persson, Wiechers, Möller, & Werner, 2019; Sánchez-García, Averfalk, & Persson, 2021).

Both of these WP4 reports are relevant for the present report since they include part-accounts for several WP5 activities which have transcended work package boundaries between WP4 and WP5, for example theoretical foundations for modelling of investment costs for district heating systems, principles and approaches used in allocation mapping of excess heat and renewable heat resources, sharing of high-resolution geospatial data, and the introduction of new concepts, such as for instance PSD (Prospective Supply Districts), just to mention a few examples.

In relation to investment cost modelling for district heat distribution systems, the D4.4 report includes the first part-account, which comprises a general introduction to the methodology (the District Heating Distribution Capital Cost model (DHDCC)), as well as results for the current year estimation (2015). The second part-account regarding this topic is given in the D4.5 report, which includes, among other, a presentation of the associated future year population and heat demand mapping (physical suitability for district heating), as well as descriptions of model improvements related to construction costs data and the Effective Width concept.

[3] WP4 title: Assessment of the role and costs of energy grids.

The main work focus during these WP4 accounts was methodology and approach development, which is also pointed out in the associated project reports. The obtained and presented results were therefore of preliminary character. The present report, together with its two complementary, and parallel, deliverable outputs, as listed below, constitute the context where the finalisation of these estimates and assessments will take on the character of final results. The concluding two public WP5 project outcomes, thus, are the following listed deliverable outputs, of which the last item is the present report:

- *D5.5: 2nd set of map layers (future years scenarios for 2030 and 2050)*
    - Update of the online visualization tool, with the second set of map layers representing the future years scenarios
    - February 2022
    - References: (Wiechers, Möller, & Persson, 2022).

- *D5.7: Spatial models and spatial analytics results*
    - This will be an online and interactive tool where the users can visualise and understand the impact of Energy efficiency measures in the 28 EU countries
    - February 2022

These two deliverables could be understood as one single result of WP5, consisting of a considerable number of geospatial layers (sEEnergies Open Data Hub, 2020), a web mapping application (D5.5), and a report on data models and their application in geospatial analyses (D5.7).

1.1. Aim and objective

To all energy efficiency potentials there is a geographic dimension. While energy statistics yield information on volumes and magnitudes on national and sectoral levels and by energy carrier, the local potentials for energy efficiency and their feasibility depend on their spatial context. Hence, in many cases the overall, national potentials are the result of processing geospatial information at the local level. This way, energy efficiency potentials are subject to geographically determined parameters like the distribution of population, building mass, industrial activities, or the distance between locations of demand and supply. Energy efficiency potentials therefore need to be mapped using geographical information systems (GIS).

Work package 5 in the sEEnergies project provides a general GIS platform that combines data sources, disaggregates results from other work packages (e.g. WP1[4], WP2[5], WP3[6], and WP4), generates data for use in scenario analyses (WP6), and disseminates results by means of online web map application and by dedicated Story Maps. The generated geospatial data is also shared on an online data sharing platform and described in various reports (Zenodo sEEnergies, 2021).

Based on the data generated and collected here, spatial analytics establish a relation between the energy efficiency potentials by magnitude and volume mapped in the various sectors. Head demands and energy savings are related to the possibility to establish district heating grids, the use of natural gas in industry is related to plant locations, and factors that drive energy efficiency in transport can be

[4] WP1 title: Energy efficiency and refurbishment strategies in buildings.
[5] WP2 title: Comprehensive Energy efficiency potentials in transport and mobility.
[6] WP3 title: In-depth quantification of Industrial energy efficiency potentials.

related to national scenarios. In addition, energy efficiency potentials are summarized and aggregated for further use in energy systems analysis and visualisation.

While some potentials can be visualised in native 100m by 100m grids (hectares), most of them are aggregated to the local level of settlements, in this context represented by Urban Areas (UA). In other instances, potentials may be summarised to NUTS3-levels and the national scale, which depends on their use within the project.

The main aim and objective of this report is to convey descriptions and informative accounts of the main approaches and methods used to develop the geospatial datasets and the spatial models that are the main contents and outputs from work package 5. It is our ambition with this work to explain how these models, and the spatial analytics performed on the basis of them, have allowed generation of results which quantify, locate, and map sectoral energy efficiency potentials and opportunities for synergies throughout contemporary EU27+UK, today and in the future, at national, regional, and local scales.

1.2. Scope and structure

The scope of the present report focusses on spatial models and spatially evaluated energy efficiency potentials, which represent the essential contents and outputs from the present work. Excluded from this scope are in-depth accounts of the parallel outputs listed above (kindly see separate accounts prepared for e.g. Peta 5.2 (Peta 5.2, 2022), the Open Data Hub (sEEnergies Open Data Hub, 2020), and the Story Maps (sEEnergies mapping team, 2022)).

The structure of the present report consists of three main sections, where Section 2 explains the spatial models that quantify and localise current and potential future energy demands in main user sectors (the building, transport, and industry sectors) and by sources and grid infrastructures. Section 3, focusses on the spatial representation of energy efficiency potentials, accounted for on local and national levels, on 1-hecare grids and by point locations, as well as by aggregations to Urban Areas, regions, and countries, were applicable. This section also includes subsections with details on spatial analyses made in association with resource allocation and the creation of the sEEnergies Index.,

The report explains the considerations, methods, and results of the processes, which emanate in the provision of quantitative outputs to be used in energy systems analyses, as well as in the distinct types of visualisations offered in the sEEnergies project. This part is addressed mainly in Section 4. The report is based on earlier reports and leaves out several technical aspects covered in these.

1.3. Earlier reports and recent findings of other projects

Besides the earlier reports from the sEEnergies project mentioned above, the Heat Roadmap Europe series of projects resulted in several publications on the mapping of heat synergy regions (Persson, Möller, & Werner, 2014), high-resolution mapping of heat demand and supply (Möller et al., 2018), the modelling of the investment costs in district heating grids (Persson et al., 2019), and the formulation of local heat supply strategies (Möller et al., 2019).

The EU-project Hotmaps (Hotmaps, 2018; Kranzl et al., 2018; Pezzutto et al., 2018) has followed a similar pathway and resulted in an open-access provision of geospatial data for heat demands. For the use in the sEEnergies project, data on age class of built-up areas were used for the distribution in the new heat demand model, see subsection 2.1.3.

For Germany, Fraunhofer ISE published “Ways to a climate-neutral energy system” (Fraunhofer (ISE), 2022), while Fraunhofer IEE published a study on transformation pathways for the German heat sector (Fraunhofer (IEE), 2022). In Denmark, a third heat plan study has recently been published (Vad Mathiesen et al., 2021), the previous two being leading publications in this field (Dyrelund et al., 2010; Dyrelund et al., 2008). In many other countries, sectoral studies have been prepared, however the need for a pan-European, cross-sectoral, and spatio-temporal study is motivated by the lack of such in the face of current challenges to mitigate climate change while securing independence of the European energy sector from imported fossil fuels.

2. Spatial models of energy demands and infrastructures

In the following section the methods used to map energy demand in the different sectors are described. Energy potentials and their relation to covering the demands are described in Section 3. Spatially evaluated energy efficiency potentials.

2.1. Residential and service sector buildings

The heat demand model originally developed in the Heat Roadmap Europe project has been

- Improved in a first step (see subsection 2.1.1) and
- in a second step thoroughly revised and improved using data from WP1 (see subsection 2.1.3)

Besides calculating a very detailed representation of current heat demands, the new model processes future heat demands. The consideration of building age classes, by area, of the built environment allows for the inclusion of energy efficiency potential by building age. That is important, as older buildings may have a higher potential than more recent structures. Furthermore, the local growth and decline of population as one of the main drivers of heat demand has been included in the modelling of future heat demands.

Based on the mapping of future heat demands, the district heating distribution capital cost model (DHDCC) has been revised and improved as it now is based on real district heating network data on the street level (detailed further in subsections 2.1.1 and 3.2 below). Costs have been calculated based on cost levels for different countries, and the model now includes distribution as well as service pipe cost calculations that use actual geospatial information on district heating infrastructures.

The heat demand and distribution capital cost data have been used to produce input to the energy systems analysis in WP6 in the form of a matrix that pairs gradually increasing levels of energy efficiency and increasing shares of district heating (see further subsection 3.3 below). This is made using a novel approach of cost-supply curves, which establish a least-cost synergetic relation between energy efficiency in buildings and the use of so-called structural energy efficiency by means of resource-efficient heating infrastructures.

2.1.1. Current year heat demands and district heat distribution capital costs 2015

Heat demands in the base year 2015 have been distributed to the 1 hectare-grid level using methods from the Heat Roadmap Europe project (Möller et al., 2018). The method has been described also in the D5.3 (Möller et al., 2020) and D5.5 (Wiechers et al., 2022) reports. Table 1 presents an overview of the 2015 datasets (layers) that are included in the Peta 5.2.

Table 1. Buildings-related and thermal grids datasets relating to the current year (2015) present at the Peta 5.2 (with annotation about original/previous web-map application versions)

Layer	Version
Cold Demand densities 2015	Peta 4.3 (Peta 4.3, 2018)
Heat Demand densities 2015	sEEnergies D5.3 layer based on HRE4 data and method (Peta5.0.1)
District Heating Distribution Capital Costs (DHDCC) 2015	sEEnergies D5.3 layer based on HRE4 data and method (Peta 5.0.1)
Current District Heating Systems (DHS)	sEEnergies D5.1 Layer based partly on HRE4 data
Prospective Supply Districts (PSDs)	sEEnergies Layer based on HRE4 data and method (Peta 5.0.1), Not included in Peta 5.2, but available at the Open Data Hub

2.1.2. Population development modelling

The modelling of local population distribution of the future is challenging, if not impossible, as many factors influence the pattern at which people locate their residence. Socio-economic development, planning procedures and by-laws, preference, the availability of land, and many more variables are impossible to anticipate and foresee, especially for all of Europe at once. Nevertheless, an estimate of how population will be distributed at local levels within urban areas and around them is required for the assessment of future heat demands and the opportunities for heat supplies.

A combination of using regional and national population forecasts with past local trends avoids the inclusion of the variables above, while it combines bottom-up empirical data from remote sensing with top-down authoritative population forecasts. Future increase or decline of population in a 1-ha grid cell depends on the past trend in this cell and its immediate neighbourhood, which is known from high-resolution population grids, which combine the extent and the intensity of urban land-use and population. The local increment is then adjusted to regional forecasts that include demographic dynamics, and finally anchored to the national forecasts used elsewhere in the project, see Figure 1.

Figure 1. Conceptual diagram illustrating the workflow of the future population model.

Future population distributions by means of raster data have been created using the national PRIMES population forecasts, regional forecasts on the NUTS3 level, and per-cell local trends from the last 15 years (2000-2015) derived from highly detailed population grids, as described in D4.5 (Persson et al., 2021). A refined version of the future population model for the final results includes the new Eurostat regional population forecast (ES, 2021), a smaller expansion (sprawl) coefficient of urban areas, as well as a refined suitability mapping of land use for future urban expansion. Suitable areas are those which are associated to urban fabric (CORINE land cover code 111, 112), industrial (121) and port (123) areas, mines, dump, and construction sites (13x), and agricultural lands (2xx) next to populated areas.

The method used to create the future population distribution in the UK differs from the EU27 method, because the regional population forecast EUROPOP2019 (ES, 2021) did not include the UK. For Great Britain, NUTS3 boundaries from 2010 and Europop13 data were used instead. Consequently, the model does not include recent population development in the UK. Figure 2 illustrates the modelling of future population distribution.

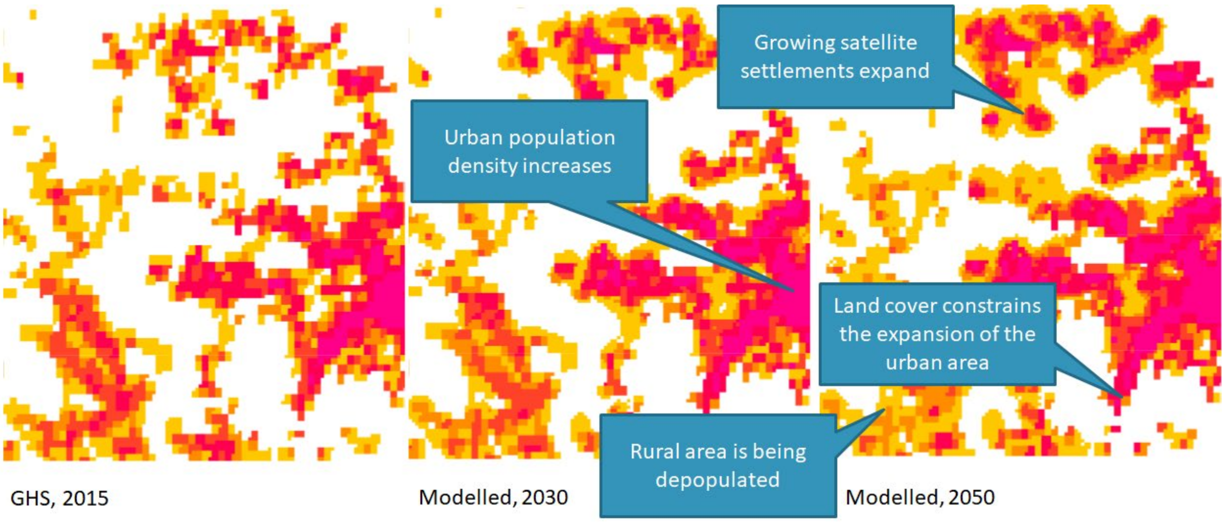

Figure 2. Mapped current (left) and modelled (middle and right) population in a 1-ha grid for a part of Potsdam, Germany. Several aspects of urban development and how the model considers these are highlighted.

2.1.3. Future year heat demand distribution

For deliverable D4.5 (Persson et al., 2021) two first draft raster datasets of future heat demand distributions (for the Baseline 2030 and 2050) have been created to further develop the district heating distribution capital costs method, see subsection 2.1.5 below. These first draft datasets proved to be insufficient to capture the dynamics in the built environment. Hence, the present report presents an improved future heat demand distribution method.

The modelling of heat demands at a 1-ha geographical resolution follows the general methodology of the Heat Roadmap Europe projects. As the sEEnergies project has emphasis on energy efficiency, which is highly influenced by the age of construction of buildings, the main difference to earlier versions is the including of building age information in the heat demand model. The age class of buildings was mapped using a dataset produced by the Hotmaps project (Mueller, 2019), which is based on the built-up vintage dataset of the Global Human Settlement Layer (GHSL) by the Joint Research Centre (JRC (EC), 2022). Also, future heat demand models include the future distribution of population. The main innovation is therefore the modelling of the extent and intensity of future heat demand distribution.

WP1 provided the national heat demands by building type (single- and multi-family housing and service-sector buildings (for further references, see e.g. (Zenodo sEEnergies, 2021)) and by building age class for different scenarios (most importantly Baseline 2030, Baseline 2050 (based on and named after the PRIMES baseline) and Frozen Efficiency 2050 Scenario). These heat demands were to be distributed to hectare cells with existing buildings and cells in which the model expects future buildings.

Using the future population raster, new built-up areas for the future years 2030 and 2050 have been identified, excluding waterbodies and other land use that is deemed unsuitable for the expansion of urban areas, see above. In a next step, areas were identified that had no Peta heat demand in 2015, but which will be built up until 2030 or 2050 .

The development of future urban area extensions is entirely based on the past development in the neighbourhood, adjusted to regional and national trends. Work package 6 in the project (WP6[7]) had decided at an earlier stage that all scenarios analysed in the context of the national matrix (see further subsection 3.3 below) are “urban densification scenarios” as defined in the transportation sector (elaborated by WP2). This is considered in WP5 by the fact that all floor areas in cells, which have been built up until 2015, are replaced until 2050. Methodologically that means that the GHS shares in 2015 are used in 2050 also, without adjustment. The heat demand that is not used in these built-up cells will be used in cells that are built up after 2015. They are identified by the future population model. Negative heat demand differences have been set to zero.

No deliberate action has been taken to increase the built-up density in existing or in new urban areas. However, by reducing the area into which urban areas can expand to two cells of 100m width, areas with a high population growth will concentrate additional population. Areas with slowly growing and shrinking populations will experience lower population densities. This suggests a lower pressure to develop new settlement areas because of lower demand. The model mimics the dynamics of urban development in more or less attractive urban areas by learning from the past development.

2.1.4. Future heat supply areas

In the Heat Roadmap Europe project, the local mapping of potential district heating areas used the concept of Prospective Supply Districts (PSD). A PSD is a coherent and contiguous area with sufficiently high heat demand densities that would make district heating technically feasible. In the most recent data model, however, the mapping of district heating, energy efficiency potentials, and potential heat sources relies on the Urban Areas (UA) that were the basis for local studies of energy efficiency and its drivers in WP2. Urban Areas are entirely based on land cover associated to urban areas and therefore independent of heat demands. They are slightly larger areas compared to PSD, and there are more of them, in particular because of a better recognition of settlements in rural areas.

The advantage is that all aspects that pertain energy efficiency on the local level now use the same geospatial entity. About 147,000 UA describe large metropolitan areas as well as very small settlements in rural areas. The UA entity includes about 89% of the present population of the EU27+UK, the remainder living scattered in rural areas. Even though it says “urban” areas, the term UA comprises all areas with land cover (CORINE) classes that belong to human settlements.

2.1.5. Modelling district heating network investments

The modelling of district heating network investments rests on the theoretical foundation and relations incorporated in the distribution capital cost model (U Persson & S Werner, 2010; Persson & Werner, 2011), which has been further developed by the WP5 partners throughout the course of the sEEnergies project (Persson et al., 2021). For the current year assessment (reference year 2015), previous results from the Heat Roadmap Europe project (Persson et al., 2017) served to illustrate the main features of the model and the corresponding results by 1-ha level for the EU27+UK (for further information, see the D4.4 deliverable report (Meunier, Protopapadaki, Persson, et al., 2021)).

Noteworthy, heat demand density classification was introduced and used as a result of the Heat Roadmap Europe project developments (Persson et al., 2019). The ability to distinguish physical suitability for district heating, based on heat demand density, turned out to be a valuable tool in the

[7] WP6 title: Modelling Energy Systems Synergies and Quantification of EEFP Impacts.

general understanding of European settlement structures in relation to heat and energy demands. The same classification is used in this work in association with the definition of local district heating shares (see further Table 7 and subsection 3.5 below).

Although the DHDCC model (the district heating distribution capital cost model) itself, as conceived and elaborated in the context of the sEEnergies project, have been subject to some important developments and improvements (most of which have been described in the D4.5 deliverable report[8] (Persson et al., 2021), the main innovation here is the future modelling made viable by the future year population and heat demand modelling described above.

The main working phases we have followed here to model future district heating network investments, that is marginal distribution capital costs for district heating systems including both distribution and service pipes, are outlined in Figure 3 at right. The first step has consisted in preparations of model input data, which, as can be seen in the principal model structure illustrated in Figure 3 at left, consists of several different data parameters. By way of the independent input data parameters, both of the intermediate input data parameters have been subject for updates and changes. For the specific investment cost, these improvement have consisted in a revised set of nation-specific constructions costs, with national updates for Germany, Austria, and Denmark (as further detailed in Table 2 below).

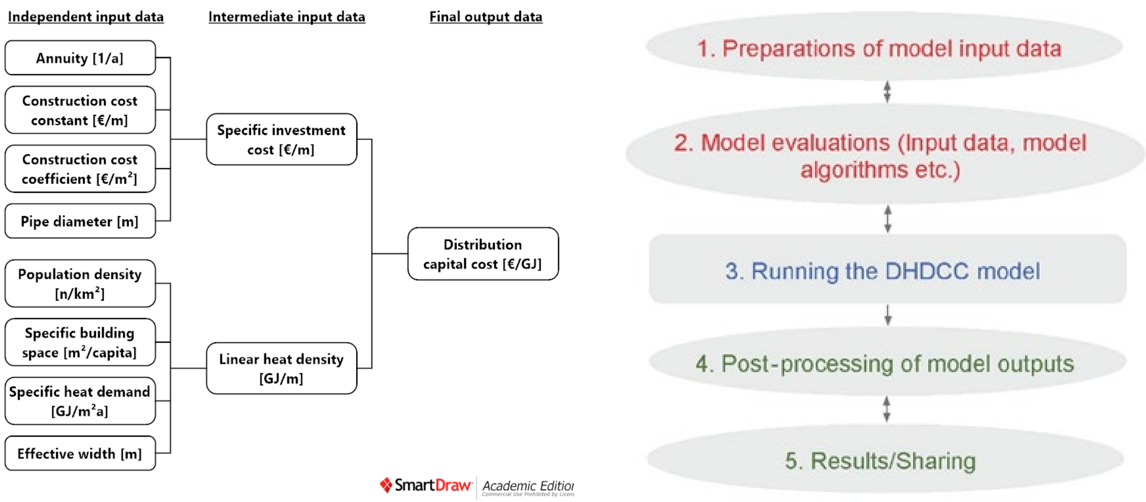

Figure 3. Principal structure of the District Heating Distribution Capital Cost model (DHDCC) with independent input data parameters, intermediate input data parameters, and final output data parameters (left), and an overview flowchart of five working phases distinguishable during the model application in the context of this report (right).

For linear heat density, this parameter has been influenced by updates relating partly to the future modelling of floor areas (population density and specific building space), and heat demands (specific heat demands), but partly also by an in-depth study to extend the empirical evidence-base for the relationship between effective width and building density (plot ratio), as documented in (Persson et al., 2021; Sánchez-García et al., 2021). In the second phase, model evaluations, the influence of input data updates on the model outputs (the final output data parameter, i.e. the distribution capital cost) have been examined and evaluated in an iterative process, in particular to understand the cause of

[8] The main model improvements in the first draft assessment of future investment costs, compared to the previous Heat Roadmap Europe assessments, was 1) use of nation-specific construction costs (rather than an EU average); 2) a wider empirical basis for the relationship between effective width and building density (plot ratio), and 3) calculation of total investment costs including both distribution and service pipes (compared to distribution pipes only in previous works).

experienced "flattening out" tendencies[9] in the draft cost curves assessment described in the D4.5 deliverable report.

In addition, a minor edit of the model algorithm was inserted to safeguard that distribution pipe diameters in no instance can be smaller than the diameter of the service pipes connected to them[10] (service pipes being attributed a 0.03-meter diameter as the model default). This was achieved by means of a cell statistics operation which selects for the service pipe diameter the minimum between the default value and the distribution pipe diameter at any given 1-ha grid cell, a new model module which can be seen in the phase three depiction (running the DHDCC model) in Figure 4.

Table 2. Construction cost curve parameters for eleven European countries, with reference to previous assessment and sources

Country Code	Range validity (Pipe diameter [mm])		Intercept	Slope	D4.5 status	Applied to	Source
	Min	Max	€/m	€/m²			
DE	25	300	664	2810	Updated	AT, DE	(AGFW, 2021)
DK			60	10000	Updated	DK	(COWI, 2017, 2020; Kristiansen, 2021; R. Lund, 2021; Niras A/S, 2018; Rambøll, 2018, 2020, 2021a, 2021b; Rambøll & Glostrup Forsyning, 2021; Trefor Varme, 2021)
ES	65	125	354	4314	Same	ES, PT	(Cuesta, 2020)
FR	65	450	*	*	Same	FR	(Roger, 2020)
HR	25	250	*	*	Same	HR, SI (x2)	(Dorotić, 2020)
HU	25	200	*	*	Same	BG, CZ, HU, PL, RO, SK	(Edit, 2020)
IT	50	400	540	2087	Same	CY, EL, IT, MT	(Denarie, 2020)
LT	70	600	71	3262	Same	EE, LT, LV	(Gurklienė, 2020)
NL	65	250	549	3370	Same	BE, LU, NL	(Schepers et al., 2019)
SE	50	400	439	4073	Same	FI, SE	(Sánchez-García, 2017; Svensk Fjärrvärme AB, 2007)
UK	25	500	549	2236	Same	IE, UK	(AECOM et al., 2017)

* Provided data on construction cost curve parameters from France (FR), Croatia (HR), and Hungary (HU), cannot be published due to confidentiality agreements.

As can be seen in Figure 4, running the DHDCC model involves raster calculations (RC) over a series of modules, which generates complete 1-ha raster grid outputs for plot ratio (PR), effective width (w), linear heat density (LHD), pipe diameters (d_a), and eventually, the network investment costs for distribution pipes ($C_{d\text{-}Dist}$), service pipes (C_{d_Ser}), and their sum-total (C_d).

The last two phases of the modelling (4. Post-processing of model outputs and 5. Results/Sharing), as outlined in Figure 3 at right, involves converting the feature class (geodatabase) raster outputs into image files and other, more compressed, dissemination and sharing formats. In the final phase, an R-studio script extracts and assembles the grid-based output data into tabular format (Comma-Separated Values files), where averages and accumulations are calculated. The first step consists of the total amount of heat that can be supplied at a certain marginal cost, a task which is carried out thanks to a zonal statistics function in the post-processing phase. This function sums the values of the

[9] In commentary, the resolve here regarding these effects has been the use of 1) decimal data types to express 1-ha raster-dataset heat demand densities (instead of integers); 2); use of specific heat demands to estimate 1-ha raster-dataset heat demand densities (rather than total heat demands per building category); and 3) incorporation of building age classes.

[10] The authors wish to acknowledge the valuable contributions made by M. Fallahnejad at the Technical University of Vienna (TU Wien) in identifying the opportunity for this model improvement.

heat demand raster in those pixels with the same geographic coordinates as the pixels in the marginal cost raster that have the marginal cost under consideration. This process is repeated for each possible value of the marginal cost in order to obtain a table with marginal costs and the corresponding heat demands. From this table and simple arithmetic calculations, it is possible to determine the cumulative heat demand, the average capital cost or the investment cost. The subsequent steps to calculate average costs for distribution and service pipes respectively, are detailed further in the Appendix (see subsection 7.1).

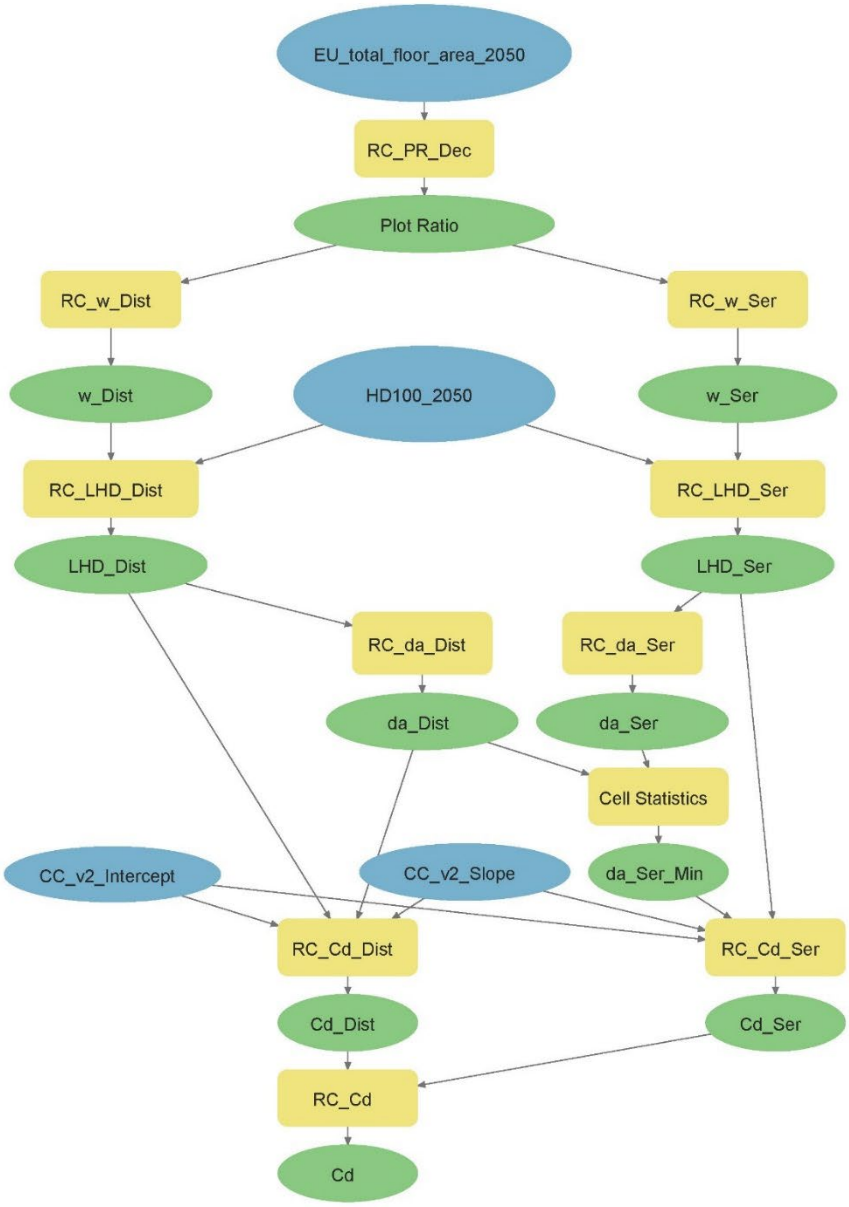

Figure 4. Detail of the third working phase of model application (3. Running the DHDCC model): Input data, calculation steps (RC meaning "Raster Calculator"), and generated output datasets, as arranged and illustrated in the ArcGIS Model Builder. The total distribution capital cost (C_d) is the sum of the specific investment cost for distribution pipes (C_d_Dist) and the corresponding specific investment cost for service pipes (C_d_Ser), all calculated based on key input data for floor areas, heat demands (HD), and construction costs (CC).

2.2. Transportation sector

Transport activity and energy demand for passenger and freight transportation were studied in work package 2 of the sEEnergies project (see deliverable report *D2.3: Report on energy efficiency potentials in the transport sector and conclusions from the developed scenarios*, available at (Zenodo sEEnergies, 2021)). The transport sector modelling on national level for each country in the EU27+UK included the following steps:

1. Creation of a reference model and establishment of a Baseline scenario with traditional urban development until 2050
2. Estimation of efficiency potentials related to urban development
3. Identification of energy efficiency related to technological development

The development of the reference model for 2017 and the baseline scenario until 2050 is based on the accumulation of transport data from a variety of different sources and combining it with the growth and technology development rates from the Baseline 2050 scenario from PRIMES (EC, 2018a, 2018b). The tool used for transport modelling is the TransportPLAN tool. It allows for the user to create detailed transport scenarios with five-year intervals from today up to 2050. For all modes of transport, the transport demand, fuel and technology mix, and vehicle and infrastructure costs were found through statistics, models, and publications, and make up the foundation of the scenario development.

The transport sector is split into two parts: passenger and freight. The transport demands of passenger cars, trucks, buses, and bicycles/walking were analyzed based on different distance bands whereas a split between international and national transport is applied for air, rail, and sea transport. The results from the TransportPLAN scenario tool are the annual transport demand in all modeled years, the energy consumption by mode of transport and type of fuel, and the costs associated with vehicles, fuel, and infrastructure.

To develop different scenarios towards 2050, TransportPLAN allows for adjustment of five main parameters:

- Annual growth of transport demand
- Modal shifts
- Market share of transport technologies
- Annual technology efficiency improvements
- Annual capacity utilization improvements.

The annual growth rates and modal shift rates for the energy efficiency scenarios were based on the D2.1 analysis (the D2.1 deliverable report titled *Report on energy efficiency potentials in the transport sector* is also available at (Zenodo sEEnergies, 2021)) by studying the following main measures to assess the impact of energy efficiency in urban planning and development:

- The urban spatial development includes measures that improve energy efficiency of the transport system by enhanced proximity to the destination i.e., reduced residential distance to the center and strong densification etc.
- Energy efficiency in transport infrastructure development curbs increases in highway capacity and airports and promotes intensification of railroad construction in urban regions
- The economic instruments propose extensive urban schemes for road tolls and parking in urban areas.

A detailed description of these measures can be found in the mentioned sEEnergies D2.1 report. The technology efficiency improvements and capacity utilizations were not varied in the assumptions made for the “Traditional urban growth” and the “Energy efficient urban growth” schemes.

The above-mentioned energy efficient urban development measures lead to an aggregated effect of around 16% transport demand reduction for passenger cars in 2050, comparing the traditional and the energy efficient urban development. A reduction by 8% is assumed to be caused by modal shifts from energy intensive modes of transport such as aviation and passenger vehicles to railways and public transport. The other half of the reduction potential is due to a reduction in the transport demand itself.

After the growth rates and modal shift rates were obtained for the urban growth schemes, four different zero-emissions transport technology scenarios were assessed in the sEEnergies project. The scenarios varied in terms of technology mix and were dominated by one technology respectively, such as hydrogen, electro fuels, biofuels etc.

These scenarios were coupled with the urban growth schemes and were ultimately compared in terms of annual systems costs and final energy demand. Table 3 below (based on D2.3, page 19) gives an overview of the different technology shares for the modes of transport analyzed.

Table 3. The share of different transport technologies (rows) in 2050 according to scenarios (columns) analysed in the context of the sEEnergies deliverable report D2.3 (Zenodo sEEnergies, 2021)

	Baseline	Biofuels	Hydrogen (H2)	Electrification and e-fuels	Electrification +
Passenger Cars	35% BEV 19% PHEV 4% FCEV 4% Gaseous 18% Gasoline 20% Diesel	35% BEV 40% Biodiesel 25% Bioethanol	35% BEV 65% FCEV	100% BEV	100 % BEV
Buses	5% BEV 36% Hybrid 21% Gaseous 38% Diesel	5% BEV 95% Biodiesel	5% BEV 95% FCEV	95% BEV 5% Electrofuels	95% BEV 5% Electrofuels
Rail	87% Electric 13% Diesel	87% Electric 13% Biofuels	87% Electric 13% Hydrogen	100% Electric	100% Electric
Aviation	3% bio-jetfuel 97% kerosene jetfuel	100% Bio-jetfuels	50% Bio-jetfuels 50% Hydrogen	19% Electric 81% E-kerosene	22% Electric 78% E-kerosene
Shipping	13% Gaseous 87% Diesel and HFO	100% Biofuels	50% Hydrogen 50% E-methanol	50% Electric 50% e-methanol	50% Electric 50% e-methanol
Trucks	1% BEV 29% Hybrid 18% Gaseous 51% Diesel	1% BEV 49,5% Biogas 49,5% Biodiesel	1% BEV 99% FCEV	27% BEV 73% E-methanol	27% BEV 73% ERS-BEV
Vans	26% BEV 1% FCEV 19% PHEV 54% Diesel	26% BEV 38% Biodiesel 36% Biogas	26% BEV 74% FCEV	95% BEV 5% Electrofuels	95% BEV 5% Electrofuels
Rail	87% Electric 13% Diesel	87% Electric 13% Biofuels	87% Electric 13% Hydrogen	100% Electric	100% Electric
Aviation	100% Kerosene jetfuel	100% Bio-jetfuels	50% Bio-jetfuels 50% Hydrogen	100% E-kerosene	100% E-kerosene
Shipping	100% Diesel and HFO	100% Biofuels	50% E-ammonia 50% E-methanol	50% E-ammonia 50% E-methanol	50% E-ammonia 50% E-methanol

Work package 2 results identified the advantages of the Electrification+ scenario in combination with energy efficient urban development. In the Electrification+ scenario, 95% of all passenger cars, all buses, and all vans in the EU27+UK are converted to Battery Electric Vehicles (BEVs). 27% of the road freight transport is converted to BEVs, while the remaining 73% are converted to BEVs with smaller onboard batteries with on-road charging support from Electric Road Systems (ERS, for more detailed information please see (Möller et al., 2020)). From the different ERS scenarios studied in work package 2, scenario 2e was chosen to be included in the modelling for the Electrification+ scenario based on a compromise between costs and connectivity.

For these reasons, the mapping and spatial-analytical activities focus on the Baseline scenario (with traditional as well as energy efficient urban development) and the Electrification+ scenario (with energy efficient urban development) including ERS scenario 2e (see also Peta 5.2). Subsection 3.1.2 presents the energy demands in combination with the resulting energy efficiency potentials.

2.3. Industry sector

At the beginning of the sEEnergies project, industrial sites were located in association with the D5.1 deliverable report (Fleiter et al., 2020; Manz et al., 2021), which combined bottom-up based and process-specific quantifications of industrial energy efficiency potentials (developed primarily in work package 3) with geographical evaluation with relation to existing and plausible district heating areas. Energy efficiency potentials were thereby distinguished both in terms of on-site energy saving potentials (reduced end-use energy demands for processes and technologies by use of so-called Best Available Technologies (BAT)), and in terms of so-called “external” energy recovery potentials by means of excess heat reuse in district heating systems. For both of these principal types of energy efficiency potentials, “internal” and external, three different levels of exhaust gas cooling temperatures (level 1: 25˚C; level 2: 55˚C; and level 3: 95˚C) were used to assess potential magnitudes.

For the representation of the then Peta 5.1 (now integrated into Peta 5.2), two excerpts from these outputs provided basis for new map layers. The first was based on assessed on-site energy saving potentials in terms of fuel and electricity demand reduction attainable by applying BAT in the considered industrial sectors: The second was based on the assessed third level of external structural energy efficiency potentials (level 3, i.e. cooling of exhaust gases to 95˚C thought to resemble 3rd generation, or contemporary, district heat distribution conditions), attainable by excess heat recoveries to current (actual) district heating systems.

Given that, for the former, certain restrictions were attached to the publication of some of the on-site fuel and electricity demand data assembled, the WP5 mapping team considered alternative approaches by which to illustrate location-specific data, without revealing point-source information. The solution to this was the concept of “energy efficiency surfaces”, which are raster map layers generated by applying various interpolation techniques to point source datasets, further complemented by additional contour line layers (see further also (Möller et al., 2020). The energy efficiency surface layers have the following pop-up information associated to them at the Peta 5.2:

- Energy saving surface: This contour layer complements the energy savings surface for on-site Best Available Technology energy savings in energy-intensive industries for the current year (sum of annual savings in PJ from all industrial sites within 50 km distance of each site).
- Excess heat recovery surface: This contour layer complements the excess heat recovery surface for industrial excess heat recovery in district heating systems for the current year (sum

of level 3 potential in PJ from all industrial sites within 50 km distance of each site). The excess heat recovery surface is illustrated in the Peta 5.2 screenshot presented in Figure 20 below.

Current and future energy demands in industry have further been modelled by WP3 in several scenarios. For the work in work package 5, two scenarios have been selected:

- IndustryPLAN-based scenario with High Energy Efficiency, Electrification and Hydrogen Fuel Shift (being an adaption of a D3.6 scenario in deliverable report *D3.6: Energy Efficiency potentials on top of reference – Report on the identified energy efficiency potentials in the industry sector, applied to the reference scenarios*) with Electrification and Hydrogen Fuel Shift, being a 100% Renewable Energies scenario
- Frozen Efficiency 2050 (as referenced in the deliverable report *D3.1: Assessment of reference scenarios for industry* (available at (Zenodo sEEnergies, 2021) and in the above-mentioned deliverable report D3.6).

This "100% Renewable Scenario with High energy efficiency, electrification and hydrogen fuel shift" is defined as follows and has only small solid biomass demands:

- High recycling
- High implementation of BAT (100%)
- High implementation of innovative measures (100%)
- High implementation of electrification (100%)
- Low/medium hydrogen fuel shift (50%)
- Remaining fossil demand shifted to solid biomass

For the mapping of industrial demands, a geospatial disaggregation to individual plants or to NUTS3 regions is required to associate energy demands, energy efficiency and available excess heat potentials to geographical locations. In absence of better data, these data were disaggregated using point-source site location data and information on verified CO_2-emissions from the EUTL (European Union's Transaction Log)[11]. Plant specific CO_2-emissions were calculated assuming proportionality between sector- and country specific fuel mixes and CO_2-emissions. Subsection 3.1.3 below presents the energy demands in combination with the resulting energy efficiency potentials.

2.4. Electricity and gas (grid) infrastructures

Main infrastructures of the gas sector are comprised of pipelines, terminals, and storages, while the main electricity infrastructures comprise transmission lines. The location of these infrastructures was mapped using open-source data.

Interesting for the future development of these main infrastructures are the changes anticipated in the future energy system. Especially for gas infrastructures, their fate is either the conversion to other gaseous energy carriers like hydrogen, or their abandonment. Whether gas transmission and distribution pipelines are subject to becoming obsolete is not studied here. However, the potential to reduce the gas for heating by means of energy efficiency in buildings and by district heating can be modelled on the local level. The same may be said regarding the use of natural gas in industry. Hence, in WP5, mapping and quantification of the potentials to reduce the use of natural gas in buildings and in industry was done, however not with explicit relation to the associated grid infrastructures.

[11] https://www.euets.info/background

3. Spatially evaluated energy efficiency potentials

The assembled and mapped energy efficiency potentials of the three different sectors provide input information for the final step in the WP5 work sequence to arrive at spatially evaluated energy efficiency potentials. For this final step, we incorporate an index, the sEEnergies index (see further subsection 3.7 below), which is established as a composite metric that allows the comparison and uniform expression, at local levels, of the sectoral energy efficiency potentials and their main underlying drivers. In order to obtain these spatially evaluated potentials, the sectoral-related potentials are first characterised at different geographical levels.

3.1. Energy Efficiency on different geographical levels

Energy efficiency potentials have been determined for the building, industry, and transport sectors by quantified current and future demands, anticipated under various scenario projections, in particular the sEEnergies baseline (BL2050) and frozen efficiency (FE2050) scenarios. The drivers and determining factors underneath these potentials, as well as some of the physical bases for these, have been mapped in a bottom-up fashion. Wherever local geography has an influence on energy efficiency potentials, the influencing factors are subject to mapping at high spatial resolution.

3.1.1. Energy efficiency in buildings

Heat demands in residential and service-sector buildings have been mapped on the 1-hectare level using the raster representations of heat demands, as illustrated for the city of Munich in Figure 5. While the growth of floor areas, the replacement of old buildings with new ones, and the renovation rate of existing buildings, determines the composition and geographical distribution of the future built environment, the intensity at which energy retrofits are carried out, as well as the energy performance requirements of buildings to be built, determine the energy efficiency potential in the future.

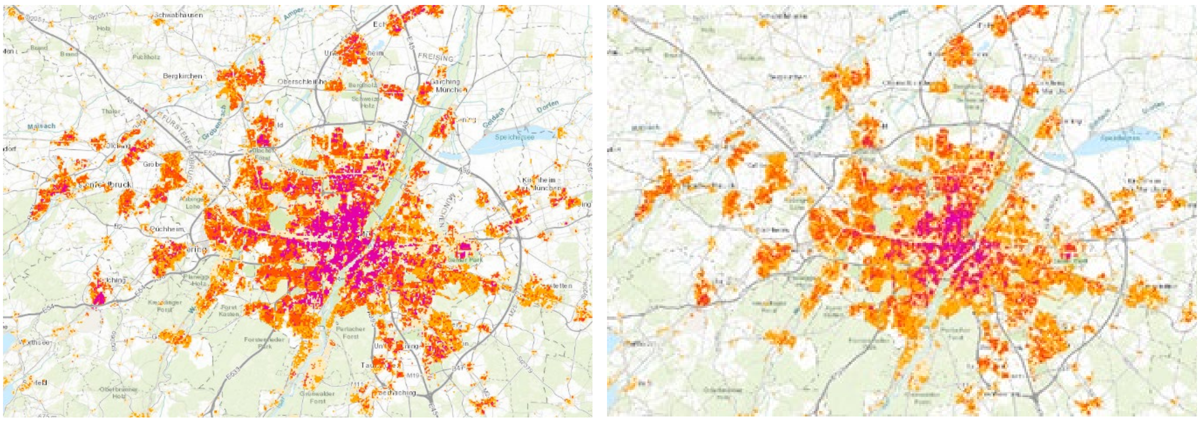

Figure 5. Map extracts showing the heat demand density in Munich under the FE2050 (left) and the BL2050 (right) scenarios respectively.

Four sets of heat demand layers have been used to model energy efficiency development in residential and service sector buildings. Point of departure is the 2015 baseline (BL2015), against which the 2050 Frozen Efficiency scenario can be compared as a business-as-usual development path. The difference between the two is the rate at which floor area increases or decreases, the replacement of old building stock, and the building energy improvements that can be expected without any further policies in this field.

The motivated energy improvements can be derived when comparing the 2050 Baseline (BL2050) against the 2050 Frozen Efficiency scenario. Floor area growth and replacement remain the same, and there are moderate efficiency improvements because of already existing policies in this field. A 2030 intermediate step has been calculated but is used for plausibility check only.

The 2050 building-related energy efficiency potential can be calculated on the 1-ha level by comparing baseline to frozen efficiency scenario datasets for this year. The result clearly shows the influence of building age on efficiency potentials and documents the necessity to include the geographical location of energy efficiency potentials in the modelling of district heating potentials.

Efficiency in buildings is also aggregated to the local level (represented by Urban Areas). This shows a clear trend in most areas with a higher potential for energy retrofits in larger cities, or the opposite, depending on the distribution of building ages. This way, the aggregated building efficiency mapped on the Urban Areas level, as indicated by the map layer shown in Figure 6, helps determining the regional distribution of potentials, and it is also being used in the sEEnergies Index.

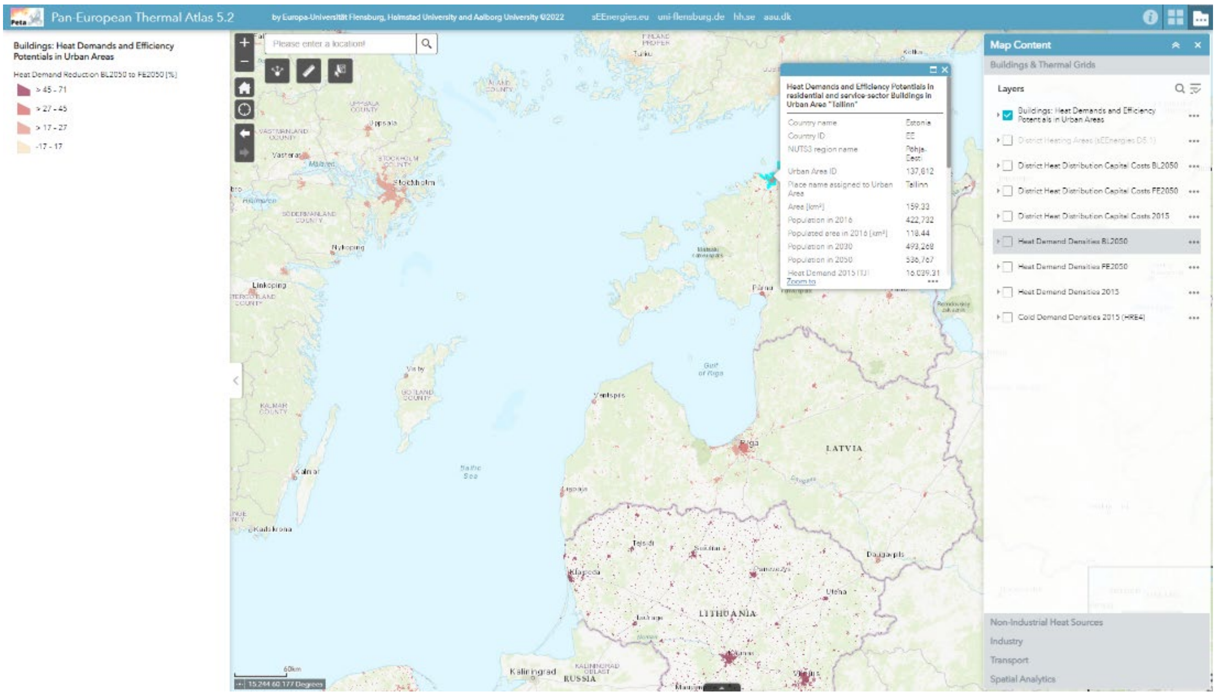

Figure 6. Screenshot map from Peta 5.2 of Urban Areas around the Baltic Sea having different energy efficiency potentials regarding the heat demand of buildings

3.1.2. Energy efficiency in transportation

The determination of transport activity demands and of transport energy demands (in scenarios as explained in subsection 2.2 above) is key for estimating the energy efficiency potentials for the transport sector. From TransportPLAN, the national energy demands of the following three scenarios for the year 2050 were exported to calculate the energy efficiency potentials, by comparing the scenarios:

- Baseline 2050 (BL2050) with traditional urban growth
- Baseline 2050 (BL2050) with efficient urban growth
- Electrification+ scenario with efficient urban growth

The energy efficiency potentials set the national final energy demands of the Baseline 2050 traditional urban growth in relation to the national final energy demands of the Baseline 2050 with efficient urban growth in a first step, and in relation to the national final energy demands of the Electrification+ scenario with efficient urban growth in a second step. The resulting dataset is presented in Figure 7 as a map layer in the Pan-European Thermal Atlas (Peta 5.2).

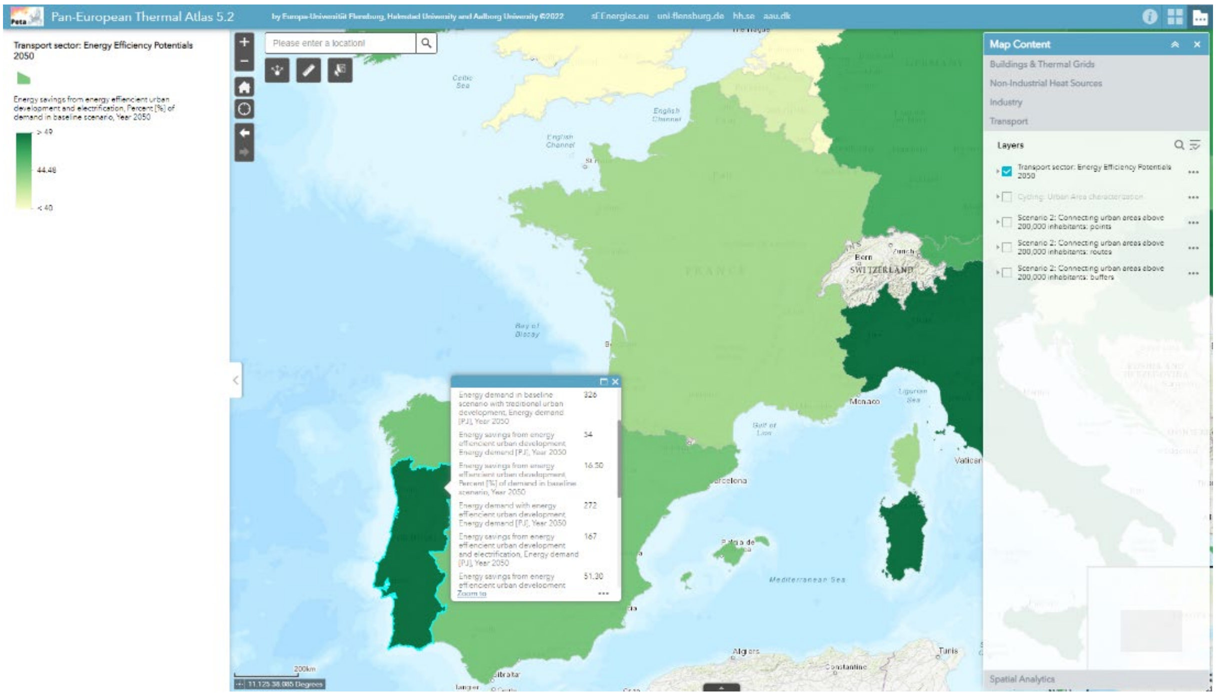

Figure 7. Screenshot from Peta 5.2 with a map layer depicting national level transport sector energy efficiency potentials in 2050.

The resulting datasets are presented also in Figure 8 as a diagram showing national final energy transport sector demands and energy efficiency potentials. Moreover, the data can be downloaded from the Open Data Hub as a csv file (sEEnergies Open Data Hub, 2020).

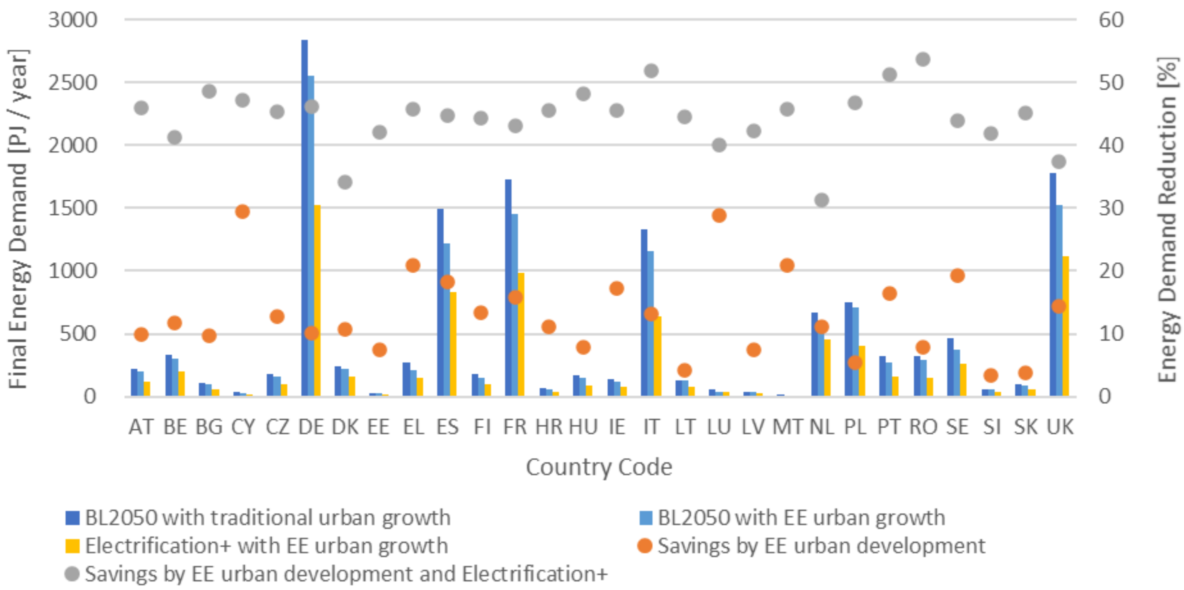

Figure 8. Diagram with transport sector final energy demands and efficiency potentials, according to BL2050 with traditional urban growth, with energy efficient (EE) urban growth, and Electrification+ scenario.

As a summary, Figure 9 shows the final energy demands and energy efficiency potential on the EU27+UK level, while also distinguishing the considered scenarios.

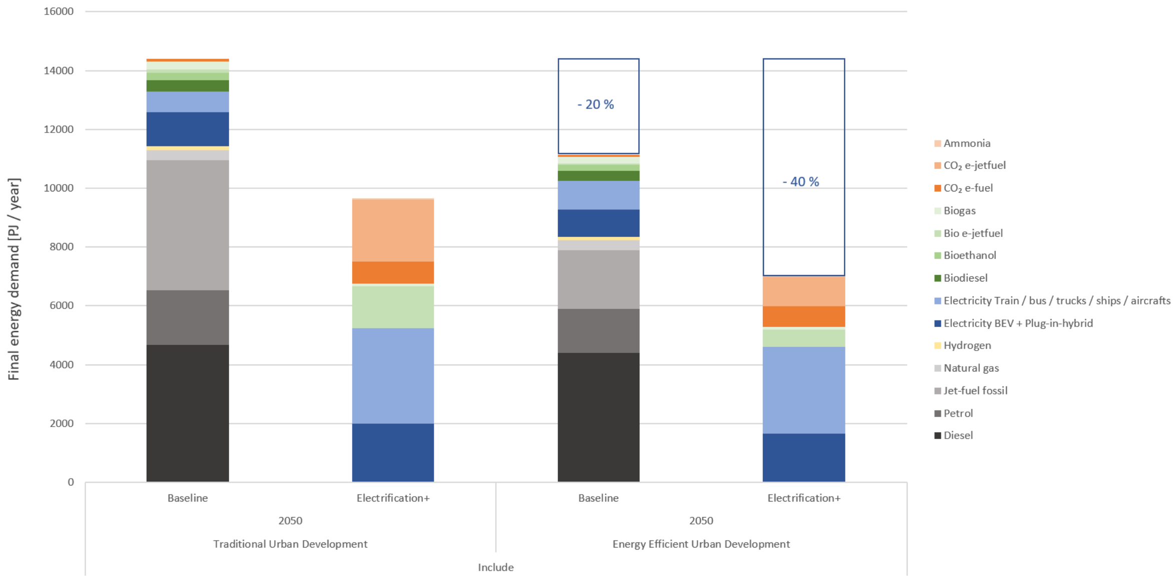

Figure 9. Transport sector energy efficiency potentials by various scenarios in comparison to baseline projections for 2050.

With regards to the transport sector, there was not sufficient scientific evidence in the input data to support a spatial disaggregation of the transport demand, the transport-related energy demands, or transport sector energy efficiency potentials to regional or local levels. The main reason for this difficulty was the primarily national level data collection prepared in WP2 and the local character of transport patterns.

Nevertheless, the Urban Areas, developed in the context of the D5.2 deliverable report (Wiechers et al., 2020), were used among other to characterise local level cycling potentials (see further (Möller et al., 2020; Peta 5.2, 2022)).

3.1.3. Energy efficiency in industry

From IndustryPLAN, national energy demands (as outlined in subsection 2.3 above) including fuel, electricity, and hydrogen demands, were extracted for the years 2030 and 2050, distinguishing the Frozen Efficiency (FE) scenario and the “100% Renewable Scenario with High energy efficiency, electrification and hydrogen fuel shift” scenario (abbreviated the “EE scenario”). For these scenario-based energy efficiency potentials, calculations were made on national levels, unlike the on-site local assessments that were performed in association with the D5.1 deliverable (Fleiter et al., 2020). In both approaches, the fuel demands are broken down on particular fuels and energy carriers, as well as by main industrial subsectors.

The national energy efficiency potentials, comparing the total final energy demand of the frozen efficiency scenario and the energy efficiency scenario, were provided for 2030 and 2050. The datasets with the final demands and the associated energy efficiency potentials are presented below in Figure 10 as a map layer of the Pan-European Thermal Atlas (Peta 5.2), with an activated pop-up showing nation-specific information, and can also be downloaded from the Open Data Hub as a csv file (sEEnergies Open Data Hub, 2020).

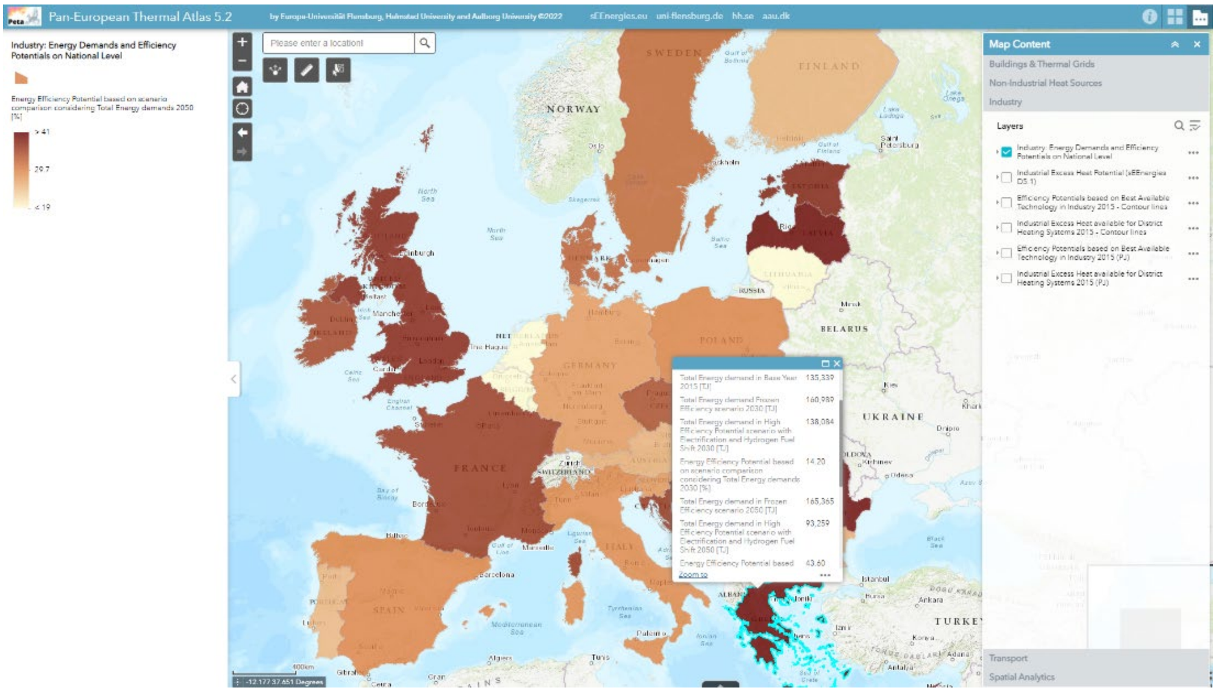

Figure 10. Screenshot of Peta 5.2 with its layer showing national energy demands and efficiency potentials in the industrial sector for the scenario years 2030 and 2050.

Figure 11 shows a diagram of the total final energy demands by EU27 member states plus the United Kingdom and the scenarios elaborated for the year 2050. The figure also includes energy efficiency potentials in precent (on secondary axis).

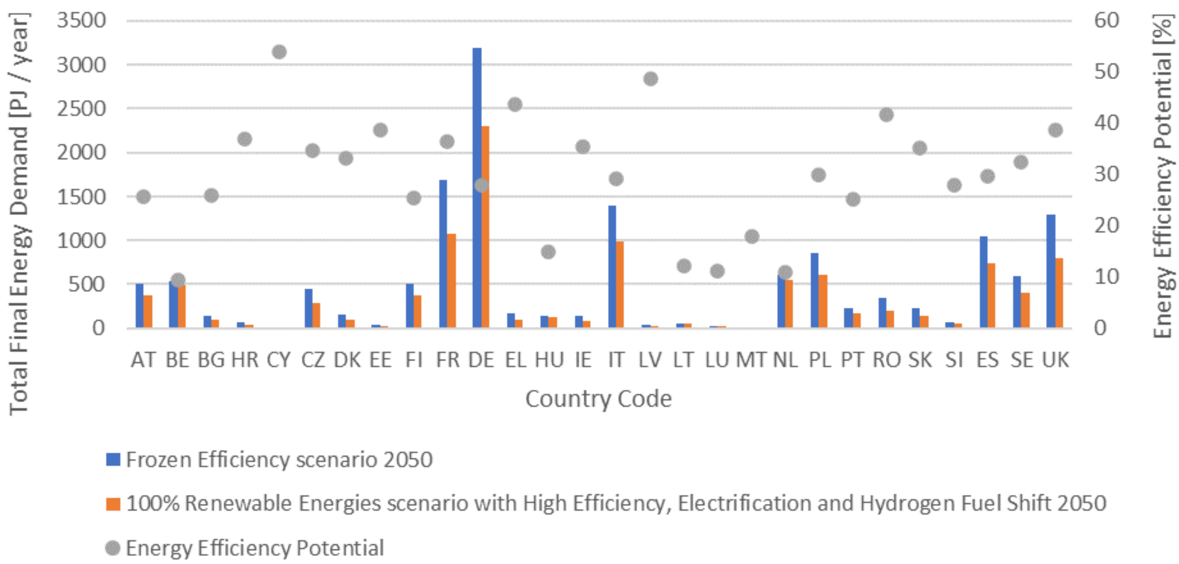

Figure 11. Diagram with final energy demands and efficiency potentials in the industrial sector in 2050 considering the Frozen Efficiency and the selected Energy Efficiency scenario.

3.2. Future district heating network investments

District heating network investment costs have been calculated at the 1-hectare level for the EU27 member states plus the United Kingdom on the basis of baseline 2050 (BL2050) and frozen efficiency 2050 (FE2050) scenario heat demand densities established for the building sector (heat demand densities of the built environment in 2050). The calculations have been made for the EU27 member states plus the United Kingdom partly treated as one single entity (grand total) and partly by treating the member states as separate national entities. The resulting output datasets consist of high-resolution map layers (shared on the Peta 5.2 as well as on the Open Data Hub), exemplified in Figure 12, and as post-processed csv-files for internal project communication (mainly to WP6) with summations and accumulations of e.g. heat demands, marginal, average, and total investment costs, as well as various other attributes (for further details on calculating average distribution and service pipe costs at certain marginal costs, and for further details of the tabular DHDCC model output attributes, see subsection 7.1 and Table 10 respectively in the appendix).

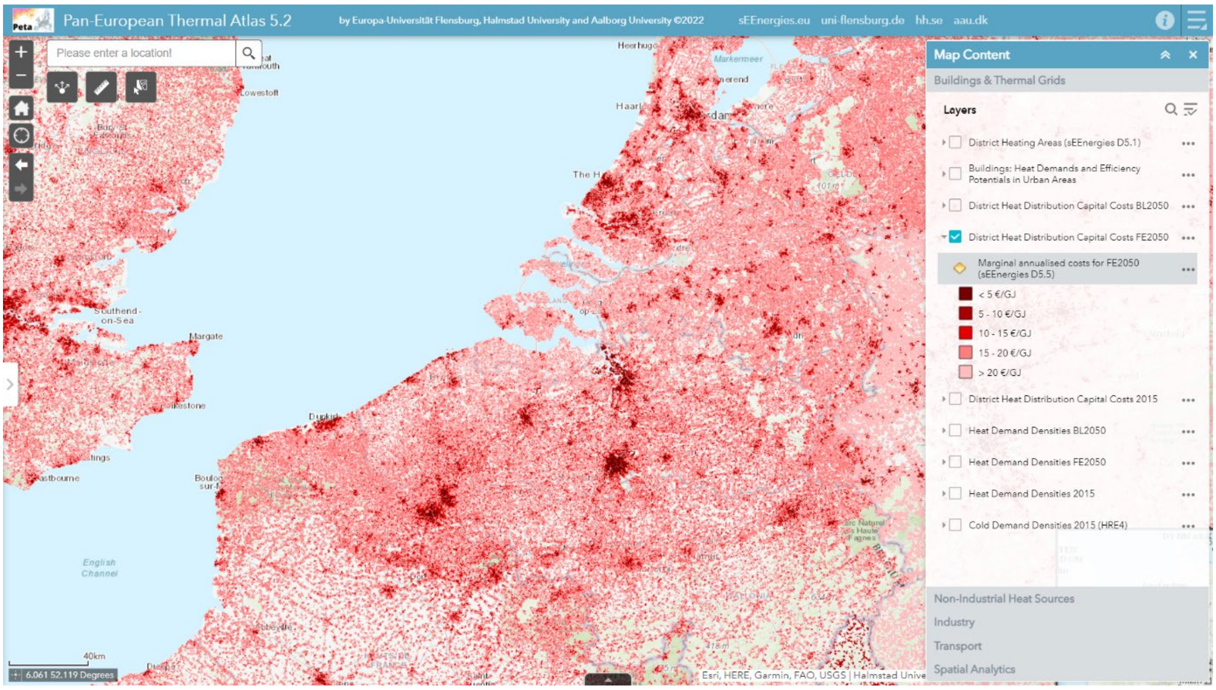

Figure 12. Screenshot from Peta 5.2 illustrating a map layers with marginal annualised investment costs for district heating by 1-hectare level resolution under the Frozen Efficiency 2050 (FE2050) scenario.

3.2.1. Grand total cost curves for EU27+UK

The main presentation format for the modelled future district heating network investment costs, are cost curves, which, generally speaking, establish a relationship between cumulative resources and the increasing costs associated with utilising these resources. The resources are in this case the heat demands to be covered by district heating. The costs are the distribution capital costs of heat distribution and service pipes, sometimes referred to as “economic suitability” for district heating, which represent the network investments.

The cost curves presented in the following tell how much of the heat demand that is economically within reach of district heating (at current day monetary value), since for each hectare cell a certain marginal capital cost has been calculated which represents the necessary investment to build a district heating network if these costs were to be annualised and prorated by the energy sold in the area (annuity used here based on a real interest rate of 3% and an economical lifetime of 30 years). Hereby, cost curves allow for the quantification of district heating potentials by cost levels, total costs, and by accumulated total heat demands, which in turn may facilitate cost sensitivities established for variations of district heating shares.

In terms of terminology, the authors have previously introduced two suitability concepts for district heating developments, which are useful for the characterisation and communication of district heating potentials (see e.g. (Persson et al., 2019)). The first of these, “physical suitability”, refers to the all-important underlying heat demand density, and the second, “economic suitability”, refers to marginal distribution capital costs, or in other words, the specific investment cost for heat distribution networks.

Physical and economic suitability for district heating have been assessed for all locations with anticipated heat demands above zero in each EU27 member state plus the United Kingdom, and, by aggregation (treating these 28 countries as one single entity) and accumulation by total heat market shares, grand total cost curves for marginal and average costs may be derived accordingly, as shown in Figure 13.

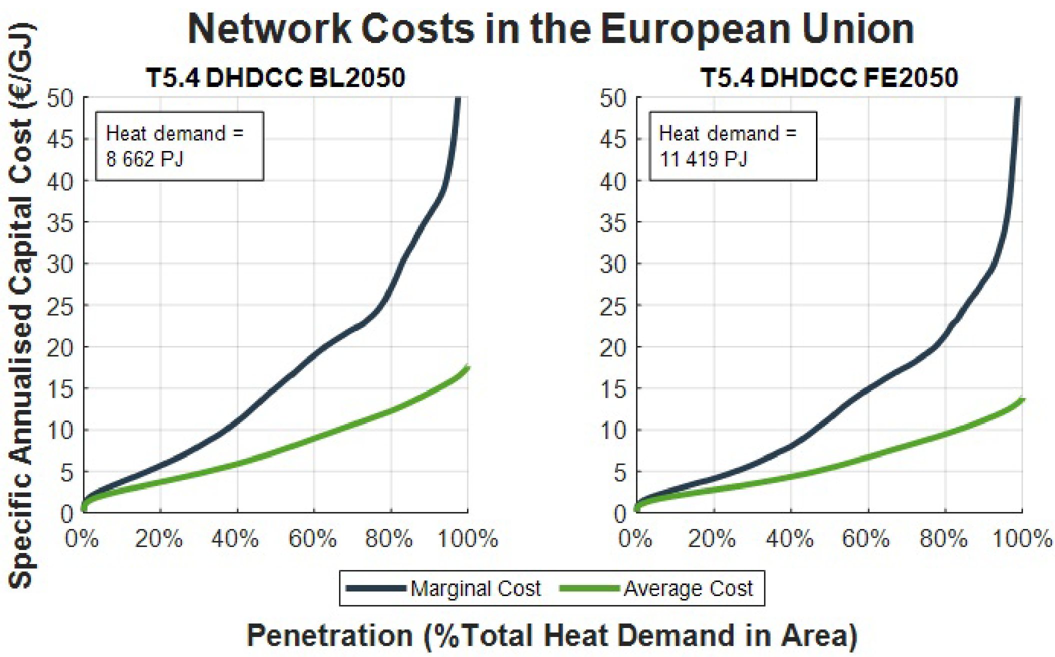

Figure 13. Grand total marginal and average distribution capital cost levels and the corresponding district heat market shares in the 27 EU Member States plus United Kingdom for BL2050 (left) and FE2050 (right) [€/GJ]. Cost levels reflect costs for both distribution and service pipes.

From Figure 13 at right, it can be seen that, as expected, the frozen efficiency heat demand scenario (FE2050), totalling at some 11.4 EJ, consists of comparably more high heat-demand density grid cells, which results in slightly lower specific costs. As further detailed also in Table 4, a 25% grand-total heat market share is associated with marginal costs of approximately 4.9 €/GJ under this scenario.

Table 4. District heating network investment costs on average for EU27+UK (modelled as one single entity) under the two sEEnergies 2050 scenarios (Baseline (BL2050) and frozen efficiency (FE2050)), by four anticipated levels of total heat market shares for district heating

DH heat market share [%]	Marginal cost [€/GJ]		Average cost [€/GJ]		Acc. heat demand [PJ/a]		Total investment [M€]		Acc. share distribution vs. service pipes [%]	
Scenario	**BL2050**	**FE2050**	**BL2050**	**FE2050**	**BL2050**	**FE2050**	**BL2050**	**FE2050**	**BL2050**	**FE2050**
25%	6.76	4.91	4.21	3.13	2166	2854	178,899	175,235	70%	72%
50%	15.04	11.39	7.34	5.41	4331	5711	622,950	605,677	64%	65%
75%	23.65	19.12	11.43	8.77	6497	8566	1,455,450	1,473,280	57%	59%
100%	377.58	305.28	17.67	13.83	8662	11419	3,000,203	3,095,727	54%	55%

For the baseline heat demand scenario (BL2050), Figure 13 (at left) and Table 4, indicates, similarly, marginal costs at some 6.8 €/GJ for an overall 25% heat market share. The total accumulated heat demand volumes corresponding to this level of district heating deployment are considerably larger in the FE2050 case (~2.85 EJ per year) compared to the BL2050 (~2.17 EJ per year).This is expected, once again, since in the frozen efficiency projection a larger amount of, relatively speaking, high heat-demand density areas are present in comparison to the baseline case.

Interestingly, it can further be seen in Table 4 that total investment volumes for the four market share levels elaborated in this context (25%, 50%, 75%, and 100%) does not change dramatically between the two scenarios. In terms of total investment costs for a 25% district heating heat market share level, the market value is expected to be found somewhere within the range between 175 to 179 billion euro (neglecting already made investments in existing systems). At the 50% level, the corresponding market value is anticipated in the interval between 605 to 623 billion euro. Included for reference, since not very realistic, 75% and 100% heat markets share levels reveal rapidly increasing total investment costs, since district heating at these levels most likely is expanded beyond reasonable feasibility thresholds. If all building heat demands in all of EU27+UK were to be supplied by district heating, this would have to happen at marginal costs above 300 €/GJ, which would correspond to total investment costs exceeding three trillion euros.

In a 2019 paper presented by the authors (Persson et al., 2019), the total market value for a 50% heat market share simulation for the EU28 at current year heat demands was estimated at 318 billion euro, a study which included investment costs only for distribution pipes, which used a less refined relationship between effective width and plot ratio, and which used only one set of EU average construction costs. Given that the accumulated share for the distribution pipe cost investment relative the costs for service pipes was found at 65% in the 50% level considered here under the FE2050 scenario, as indicated in the far-right column in Table 4, a 394-billion-euro market value may be said to correspond to the referenced 2019 numbers. Noteworthy, the relative accumulated share of distribution pipe costs versus service pipe costs decreases with higher levels of heat market shares. This may be explained by the fact that relatively fewer distribution pipes, but relatively more service pipes, are needed as more and more buildings are connected to the distribution system.

3.2.2. Cost curves for the EU27 member states and the United Kingdom

Similar to the grand total cost curves presented above for the EU27+UK on average, treated as one single entity, nation-specific cost curves for the baseline 2050 (BL2050) scenario, see Figure 14, Figure 15, and Figure 16, together with tabular outputs considering a 25% district heating heat market share under both scenarios, see Table 5, are presented below in this subsection. Additional cost curve graphs reflecting the frozen efficiency (FE2050) scenario, as well as corresponding cost curves in the unit [€/MWh] are also presented in the appendix (see e.g. subsection 7.4). A corresponding tabular output considering a 50% district heating heat market share under both scenarios are as well as presented in the appendix, see Table 11. District heating network investment costs for the EU27 member states (MS) plus the United Kingdom (UK) under the sEEnergies 2050 scenarios (Baseline (BL2050) and frozen efficiency (FE2050)), at anticipated 50% national heat market shares for district heating, in subsection 7.3).

As visible in the mentioned figures, national marginal and average cost curves display a wide range of different behaviour. The influence of (low) national-specific construction costs is palpable for countries like Estonia and Croatia (Figure 14), and Latvia and Slovenia (Figure 15).

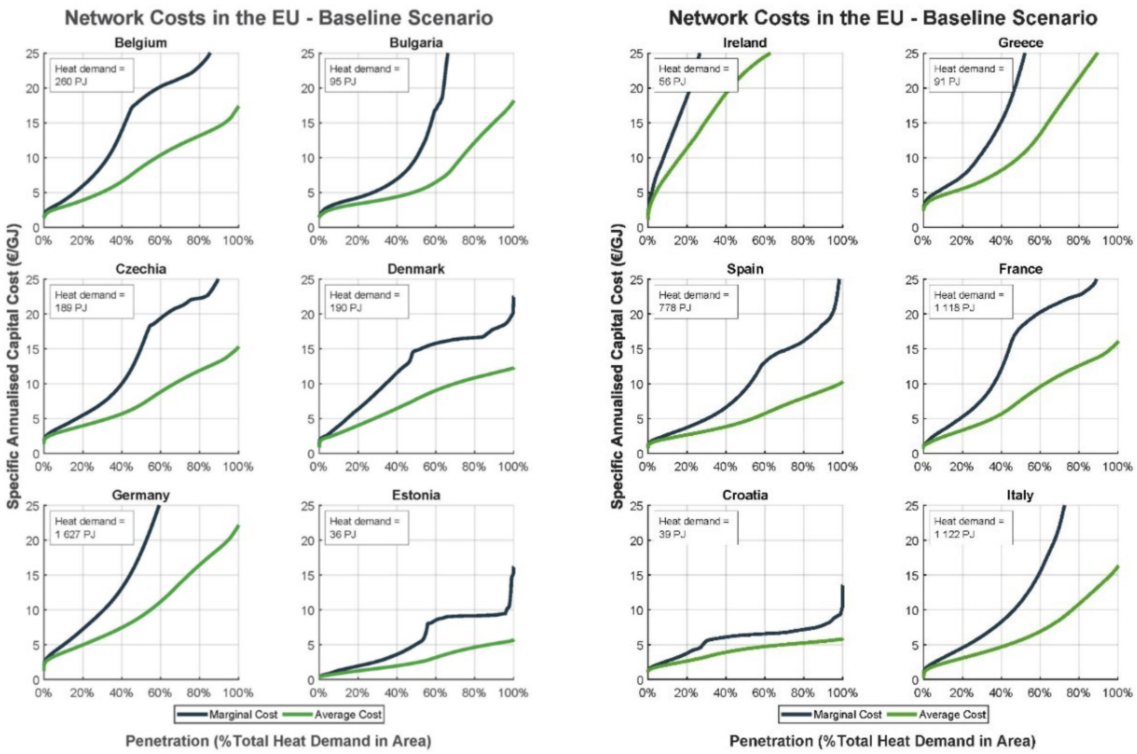

Figure 14. BL2050 cost curves for BE, BG, CZ, DK, DE, EE (left) and IE, EL, ES, FR, HR, IT (right) [€/GJ].

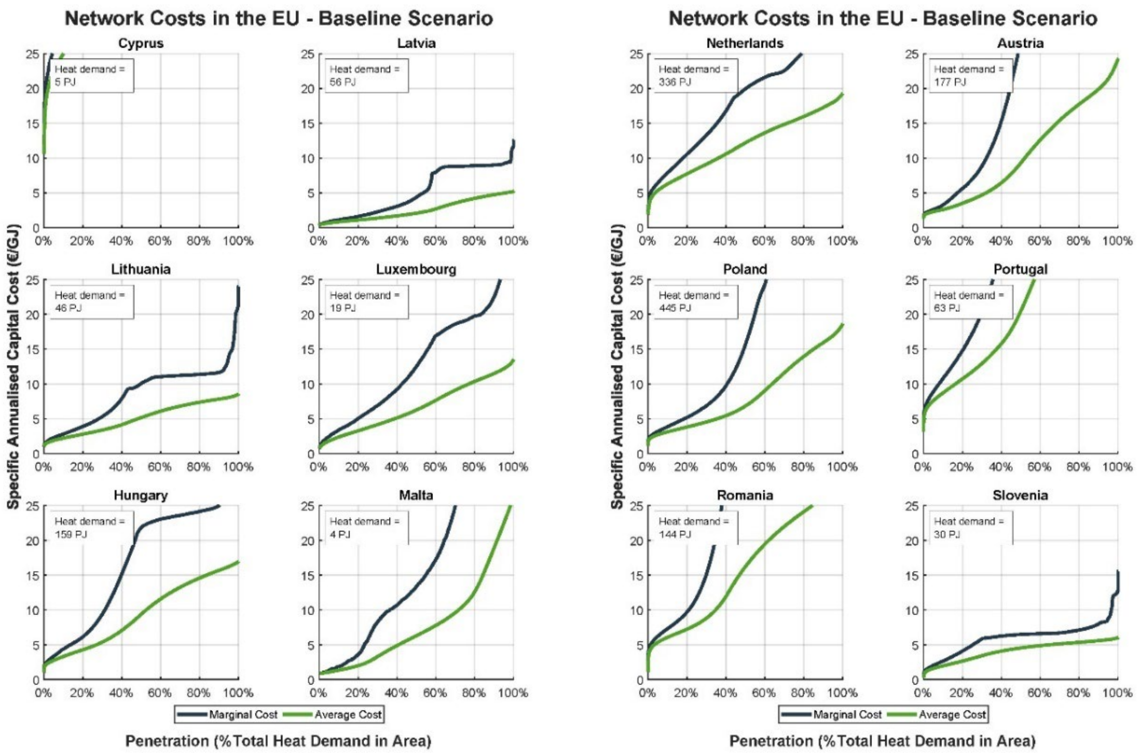

Figure 15. BL2050 cost curves for CY, LV, LT, LU, HU, MT (left) and NL, AT, PL, PT, RO, SI (right) [€/GJ].

In other instances, such as for example in Ireland, Cyprus, and Portugal, introduction and expansion of district heating, already at heat market shares well below 10%, seems to be associated with comparably high specific investment costs. From Figure 14 and Figure 16 it is further observable that so-called mature district heating countries, like those here representing Scandinavia (Denmark, Finland, and Sweden), are associated with marginal costs in the order of four to eight euros per gigajoule for 25% heat markets shares under the BL2050 scenario, see Table 5 (countries average at 9.0 €/GJ). Correspondingly, marginal costs in the order of ten to twenty euros per gigajoule are expected for 50% heat markets shares under the same conditions, see Table 11 (countries average at 20.7 €/GJ).

Table 5. District heating network investment costs for the EU27 member states (MS) plus the United Kingdom (UK) under the sEEnergies 2050 scenarios (Baseline (BL2050) and frozen efficiency (FE2050)), at anticipated 25% national heat market shares for district heating

MS	Marginal cost [€/GJ]		Average cost [€/GJ]		Acc. heat demand [PJ/a]		Total investment [M€]	
Scenario	BL2050	FE2050	BL2050	FE2050	BL2050	FE2050	BL2050	FE2050
AT	6.96	5.44	4.05	3.17	44.2	56.3	3,513	3,502
BE	7.3	5.06	4.44	3.13	64.9	86.5	5,649	5,303
BG	4.72	4.04	3.59	3.09	23.7	27.0	1,669	1,633
CY	46.13	34.97	32.05	24.59	1.3	1.9	835	898
CZ	6.29	4.65	4.36	3.30	47.3	61.0	4,043	3,941
DE	8.48	5.56	5.56	3.72	407.2	569.1	44,343	41,520
DK	7.56	6.66	4.61	4.05	47.5	55.6	4,287	4,416
EE	2.25	1.82	1.42	1.20	9.0	12.1	249	283
EL	8.79	8.12	6.04	5.63	22.8	23.8	2,695	2,619
ES	4.3	3.76	2.94	2.59	194.6	223.5	11,195	11,342
FI	4.06	3.04	2.59	1.91	44.8	52.5	2,275	1,972
FR	6.33	4.89	3.82	2.95	279.4	370.1	20,911	21,399
HR	4.38	2.96	2.95	1.78	9.7	23.0	559	801
HU	7.49	4.62	4.78	3.04	39.9	54.8	3,736	3,267
IE	23.27	10.25	13.26	5.93	14.1	23.3	3,657	2,705
IT	5.34	4.28	3.45	2.78	280.5	335.5	18,961	18,313
LT	4.52	2.61	3.08	1.75	11.5	25.1	693	862
LU	5.96	3.01	3.71	1.96	4.9	10.7	353	409
LV	1.92	1.45	1.23	0.97	14.0	18.7	338	353
MT	5.72	3.81	2.52	1.78	0.9	1.1	47	38
NL	11.88	9.08	8.43	6.51	84.0	106.3	13,877	13,567
PL	5.96	4.52	4.17	3.13	111.3	162.5	9,106	9,983
PT	17.24	15.57	11.77	10.63	15.7	17.8	3,632	3,706
RO	11.78	8.01	7.92	5.68	35.9	47.5	5,571	5,289
SE	6.33	4.74	3.84	2.90	60.4	73.2	4,548	4,162
SI	4.93	2.59	3.03	1.60	7.5	17.4	444	545
SK	13.16	5.4	8.38	3.49	14.3	42.3	2,354	2,899
UK	9.12	6.12	5.73	3.84	275.1	358.2	30,904	26,961
Max. value	**46.13**	**34.97**	**32.05**	**24.59**	**407.2**	**569.1**	**44,343**	**41,520**
Min. value	**1.92**	**1.45**	**1.23**	**0.97**	**0.9**	**1.1**	**47**	**38**
Avg. value	**9.01**	**6.32**	**5.85**	**4.18**	**77.4**	**102.0**	**7,159**	**6,882**

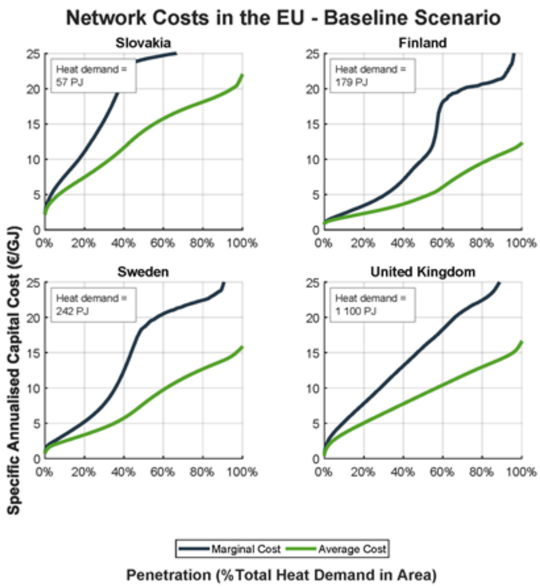

Figure 16. BL2050 cost curves for SK, FI, SE, UK [€/GJ].

3.3. The national matrix: Shares of energy savings and district heating in buildings

Using the cost curve approach, the heat infrastructure costs for potential shares of district heating and for different rates of energy efficiency in buildings, as well as expansion of heat pumps, were established in the form of a matrix, the "national matrix", as principally outlined in Table 6. This matrix was established for each member state of the EU and the UK. It allows for pairing energy efficiency in buildings and in heat supply by telling how much of the remaining heat demands (after implementing energy efficiency measures in buildings) that can be covered with district heating. The remaining heat demands not physically or economically viable to meet with district heat supplies, need to be covered with technologies like heat pumps and other individual heat alternatives.

The matrix approach allows determining the balance of heat savings and heat supply for each country. This is determined by looking at a combination of total socio-economic costs for the entire energy system, resource demands and other technical feasibilities such as electric grid balancing. Heat saving and supply results are developed from a full energy system analysis to incorporate all the interconnected dynamics in the energy system in which buildings and their heat supply are a part of. The full energy system analysis belongs to dedicated work package 6 activities, but in this respect, there is a direct interlinkage with the activities in work package 5, where the spatial mapping and quantification of feasible expansion levels of future district heating provides a key input.

Table 6. Principal outline of the national matrix with pairing of energy savings in buildings and heat markets shares for heat pumps (HP) and district heating (DH)

	Heat savings	**0%**	**-10%**	**-20%**	**-X%**
HP/DH coverage of heat demand					
100%/0%		Total energy system costs	Total energy system costs	….	…
…./….		Total energy system costs	….	…	…
30%/70%		….	….	…	…

3.4. Converting natural gas areas into district heating areas

The conversion of heat supply currently covered by natural gas to alternative supply forms such as district heating requires spatial analysis of the heat demand densities in potential heat supply areas. Using thresholds for the heat demand density, see Table 7, which is technically required for modern district heating systems, the potential district heating share within urban areas can be modelled. Using different thresholds of 50 TJ/km² for current systems, 35 TJ/km² for advanced systems, and 20 TJ/km² for so-called 4th generation district heating systems (Averfalk, Ottermo, & Werner, 2019; Averfalk & Werner, 2017, 2018; H. Lund et al., 2014; H. Lund et al., 2018; H. Lund et al., 2021), the potential share of district heating in each urban area is calculated for the Baseline Scenario and the year 2050.

The potential district heating share provides an indicator and the basis for a quantification of the future natural gas demand, which can be replaced in residential and service sector buildings. National natural gas demands used in the residential and service sectors (IEA, 2019) were distributed to those buildings, which are located within NUTS3-district that have access to gas transmission infrastructure. As there is no Europe-wide dataset on the coverage of natural gas distribution, it was assumed that NUTS3-districts located less than 50 km away from nodes in the gas transmission networks have distribution infrastructures. This includes all of continental Europe but not Northern Sweden, Finland and the Highlands and Islands of Scotland as well as Corsica. The transmission grid data used came from the EMAP project and available by the SciGrid conference open data initiative. Natural gas infrastructures were mapped for each NUTS3 district by counting the number of nodes in the natural gas pipelines, which is assumed to be a good indicator for the presence of natural gas distribution networks.

In industry, natural gas demands in individual facilities are estimated using sector- and country specific natural gas demands modelled in the IndustryPLAN model in WP3, which are distributed to about 3,700 individual plants that participate in the EU Emission Trading System using verified CO_2-emissions from the year 2019 and country- and sector specific CO_2-emissions. To assess the potentially saved natural gas consumption, the difference between the Baseline 2050 and the 2015 scenario was used, resulting in a saved gas potential for each facility. Only about 80% of the natural gas consumption could be allocated this way, because not all the industrial plants are subject to emission trading.

A European natural gas hot spot analysis was carried out for NUTS3-areas, which includes the potentials to replace gas for heating, and in industry. Another parameter was the presence of natural gas infrastructure. Hot spots are those areas, which comprise high gas demands, high replacement potentials, and a strong presence of gas infrastructure.

3.5. Definition of local district heating shares (in Urban Areas)

Potential district heating shares and demands can be estimated for potential supply areas in two ways. First, the technical potential may use a minimum threshold of heat demand density, see above. Second, a maximum marginal cost level can be used as a criterion for the economic assessment of district heating potentials. The economic assessment is difficult, as only the costs of local district heating infrastructures (distribution and service pipes) are included and the costs of heat production, transmission and balance of plants are excluded. In addition, a general maximum cost threshold for all Europe disregards the different cost levels and purchase power parity in heating costs and heat supply. Local district heating shares were therefore modelled using technical considerations of heat demand density thresholds alone.

Heat demands (current 2015 and Baseline 2050) were summarised for intervals of heat demand densities (heat demand classes 0 to 5 as illustrated in Table 7) in each urban area using zonal statistics in ArcGIS Spatial Analyst.

Table 7. Classification of heat demand concentration levels and suitability for district heating (DH) by use of heat demand density thresholds

Heat demand class	Heat demand density threshold [TJ/km²]	Comment
0	Less than 20	Rural areas, extremely low densities, no DH possible
1	20 – 35	Very low-density areas, potential for 4th generation DH
2	35 – 50	Low-density areas, advanced DH possible
3	50 – 120	State of the art medium density areas, DH feasible
4	120 – 300	High density areas, DH likely
5	More than 300	Highest density areas, DH highly likely

The resulting heat demands by density class have been joined to the Urban Areas feature class and made available on the Open Data Hub. Figure 17 shows a screenshot of the resulting map layer with potential district heating shares considering different thresholds.

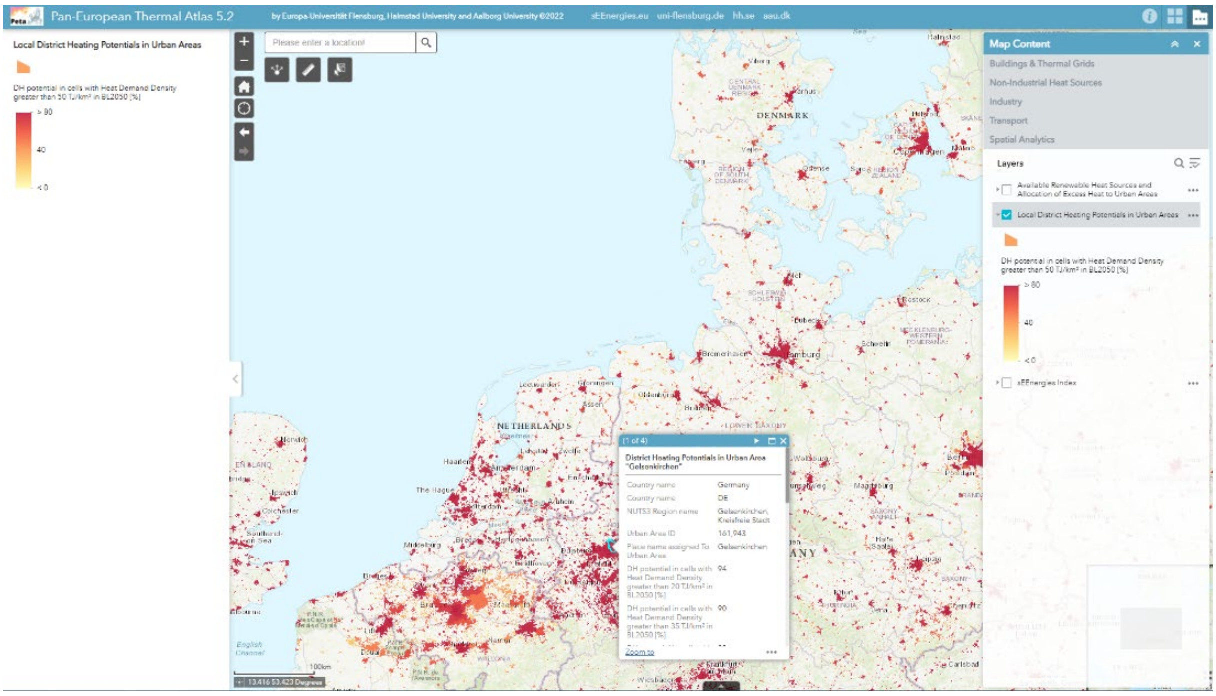

Figure 17. Screenshot of Peta 5.2 showing its Local District Heating Potentials layer.

3.6. Allocation of locally available heat resources to Urban Areas

The allocation of geographically distributed heat supply from excess and renewable sources to potential local heat supply areas is a first step towards the formulation of local heat supply strategies, which utilise energy efficiency and renewable energy. It allows for the bottom-up quantification of locally available sources for use in national heat supply analysis, as spatial constraints are included, to which top-down approaches are oblivious.

3.6.1. General remarks

The excess heat from industrial or other activities, and the local renewable energy resources influence the potential local heat supply. All of these are defined by local conditions, and therefore subject to geospatial analysis. Potential sources of heat from excess heat activities and from solar, geothermal and biomass sources have been spatially allocated to Urban Areas, within which potential district heating areas can be developed. The allocation considers local availability and proximity, while it disregards the choice of heat sources in a "Smart Energy Systems" approach, or the economic aspects of utilising local sources.

3.6.2. Defining potential shares of district heating

The potential to develop district heating systems is assessed using the approach described in section 3.5. As a conservative estimate, thresholds of more than 50 TJ/km² were used to identify potential district heating areas that participate in the allocation of excess heat.

Coherent and contiguous heat supply areas are delineated from raster maps that show heat demand density. In the sEEnergies project, the earlier used Prospective Supply Districts (PSD) from the Heat Roadmap Europe project were replaced by the Urban Areas, which have also been used to generate local transport characteristics in WP2. There are 147,068 Urban Areas (UA) in the EU27+UK. These reach from very small settlements of 3 ha area to parts of large cities. Large UA have been split by the NUTS3 administrative layer, which means that large cities have been divided into smaller units, and that agglomerations of urban areas can be identified as individual administrative districts.

Generally, the size and extent of UA reflect the presence of independent, coherent, contiguous areas separated by at least a 200-meter distance to their neighbours. All areas with heat demand densities above 50 TJ/km² offer the opportunity to develop heat infrastructures. There are 64,434 UA that are considered potential DH areas. Although it is attractive to use economies of scale in the development of DH, potential clustering of UA to greater DH systems is not considered here.

3.6.3. Solar thermal

The potential for solar thermal district heating depends on the available solar irradiation, the available land area for a collector field, and the system integration. Land area and system integration have not been considered here, as they highly depend on local preferences. Solar radiation has been modelled using global horizontal irradiation (GHI) from the Global Solar Atlas by the World Bank Group and Solargis (World Bank Group, ESMAP, & Solargis, 2022). For each UA, the mean GHI was calculated and assigned to the UA feature class.

3.6.4. Geothermal

The potential for using deep geothermal sources depends on the geology of the area. Five layers resulting from the EU-GeoDH-Project were used (GeoDH, 2014):

- Temperature at 2000m greater than 90°C
- Heat flow density greater than 90 mW/m²
- Hot sedimentary aquifer
- Neogene basins
- Other potential reservoirs

While it is not possible to estimate geothermal potential directly from these layers, in combination they show a likelihood of present geothermal heat below. The geothermal resources have been allocated using an intersect operation between a union of the five GeoDH layers and the UA layer.

3.6.5. Biomass

The potential of bioenergy from agriculture and forestry biomass is limited to straw and wood residues and has been derived from the results of the EU-project S2Biom, which has quantified, among others, technical potentials on the NUTS3-level (S2Biom, 2016, 2022). If using biomass for energy purposes, economies of scale and logistical effects should be considered. The most productive forestry operations may produce large amounts of wood residues, which should be used at large scale, and not necessarily for local district heating. The same accounts for residual straw. However, for small-scale district heating in rural areas, and outside productive forest management areas, the local procurement of wood and straw residues may be an advantage.

Consequently, mostly rural settlements may see a greater use of wood than predominantly urban areas, and areas with highly productive forestry operations may prioritise the export of wood residues to other uses like the replacement of fossil fuels. Overall, the idea is to use biomass for higher-value purposes than just combustion; however, where no options exist for advanced district heat generation technologies – either because of size of plant, socio-economic considerations, or the absence of other renewable energy sources – the use of local biomass should be an option to secure energy justice.

The technical potentials of straw and wood per NUTS3-district were distributed to the immediate neighbourhood of each UA. First, using the CORINE land cover dataset for 2018, straw-producing areas were defined as "non-irrigated arable land" (CLC code 211) and it was assumed that all straw originates from agricultural production on these areas. Likewise, all types of forest, "Broad-leaved Forest" (CLC 311), "Coniferous Forest" (CLC 312) and "Mixed Forest" (CLC 313), were characterised as productive forest, which is realistic for most parts of Europe.

Then the wood and straw resources per NUTS3-level were distributed to all arable land and forest cells within each NUTS3 district. The result is a continuous biomass map with a raster resolution of 100 meters, which assumes the same production density in the forest and arable land areas across each NUTS3 district. The resulting map implicitly recognises the regional diversity in soil types, climatic condition, and management practices in agriculture and forestry across Europe. Only sustainable, i.e. residual, sources are included.

The next step regards the allocation to individual UA. Here, the immediate neighbourhood of each UA was defined by proximity. Thiessen polygons define the area from which a given amount of biomass is allocated to the nearest UA. The allocation is exclusively by distance, it disregards the availability and the required geographical area from which all required biomasses will be sourced while assuming the shortest transport distance. The last step is to summarize for each UA the available biomass by Thiessen polygon using zonal statistics.

3.6.6. Wastewater treatment plants

Wastewater treatment plants (WWTP) emit treated water at temperatures above the ambient and they can be considered a source of heating to be utilised by heat pumps. The excess heat potential from wastewater treatment plants has been quantified by the ReUseHeat project (ReUseHeat, 2018), in the form of a point layer with 23,189 individual plants in the EU28.

For the allocation, the accessible excess heat potential (QH) at the most suitable (and selected) curve fit projection from the model dataset to the full WWTP population dataset (Nr. 4) was used. In this potential, the EHI (the European Heating Index (Werner, 2006)) has been used to adjust for other than Swedish yearly average climates (the model dataset was based on Swedish conditions), plus: accessible heat, meaning at heat pump condenser-side at average Coefficient of Performance (COP) of 3.0 as an annual average.

The plants were allocated to Urban Areas according to their size and distance. First, the area nearest to each WWTP was mapped using Euclidean Allocation in raster analysis. By calculating the maximum of total heat demands in each of the Urban Areas that intersect the allocation areas, the excess heat from each WWTP was allocated to the largest potential heat consumer in the immediate neighbourhood.

3.6.7. Industrial excess heat activities

The D5.1 industry dataset comprises 1,842 locations of industrial plants and their modelled excess heat potential at several temperature levels (Fleiter et al., 2020). 1,597 locations have a positive potential at level 2 (55°C temperature). These plants are to be allocated to nearby UA in a fashion that maximises the heat utilised at each location while minimising the required transmission pipelines. For this purpose, a network-based method was used, addressing the allocation of excess heat to potential district heating areas by means of the Maximize Capacitated Coverage Problem (MCCP) using ArcGIS Desktop 10.7.1 with Network Analyst.

Industrial plants are the facilities in the MCCP; all of them must be located. The plant data stem from the above-mentioned D5.1 dataset, and the weight and capacity of the plants was defined to be the excess heat in TJ at a temperature level of 55°C. Demand locations are UA, which are defined potential district heating areas if they have hectare gird cells with a heat demand density of more than 50 TJ/km², which is here assumed as a conservative estimate. The heat demand to be supplied is the sum of all heat demands in these cells. (Möller et al., 2019) have suggested a method that also included a baseload share and district heating grid losses; however, these are not considered here.

Because in Network Analyst demands cannot be split between facilities if their demand exceeds facility supply, the UA were split geographically. This was done using a 2 km grid (ES, 2022). UA with a heat demand greater than 1 TJ were split using tessellations of 2 km grid points located 1 km inwards from the boundary of UA polygons, which were converted to Thiessen polygons, for which the heat demands were split and summarised. 60,434 locations were loaded.

As a road network, the gRoads road network database has been used (Center for International Earth Science Information Network - CIESIN - Columbia University & Information Technology Outreach Services - ITOS - University of Georgia, 2013), which offers a compromise between detail and processing time for all locations within the EU27+UK. A cut-off distance of 50 km was applied. This is the maximum distance from which heat can be transported from an excess heat source to a DH location.

The solution of the allocation process is the amount of excess heat in each facility that can be utilised in the nearest UA, which comprise potential and existing district heating systems. Likewise, the results include information which UA may receive excess heat. Allocation only considers all the heat demand in an UA.

In total, 412 PJ of out 3,959 PJ of heat demands in urban areas with heat demand densities above 50 TJ/km² is within 50 km and can be allocated to available excess heat capacities in industry, which sum up to 500 PJ in the EU27+UK. That means that industrial excess heat can cover approximately 10% of district heat potentials, while 82% of excess heat can be used. This is in line with earlier findings in the Heat Roadmap Europe project.

The remainder of industrial excess heat cannot be allocated as local supply exceeds demands, while the majority of potential or existing district heating areas is out of reach for industrial excess heat, as only 15,686 out of 64,434 (24.3%) urban areas with sufficient heat demand densities can be reached and supplied by industrial excess heat.

While the solution of the MCCP is a least-cost allocation of limited resources to a limited local area, transmission pipe costs are not included here. One could argue that exceptionally long pipes to connect small sources are deemed unfeasible.

3.6.8. Preparing heat supply strategies for Urban Areas

From the above analyses, the conditions to use geothermal and solar heat, the availability of excess heat from wastewater treatment plants and from industrial locations, and the bioenergy amounts from nearby fields and forest, have been allocated to UA. The result is an extensive table, which allows for the formulation of bottom-up heat supply strategies, as visualised in Figure 18.

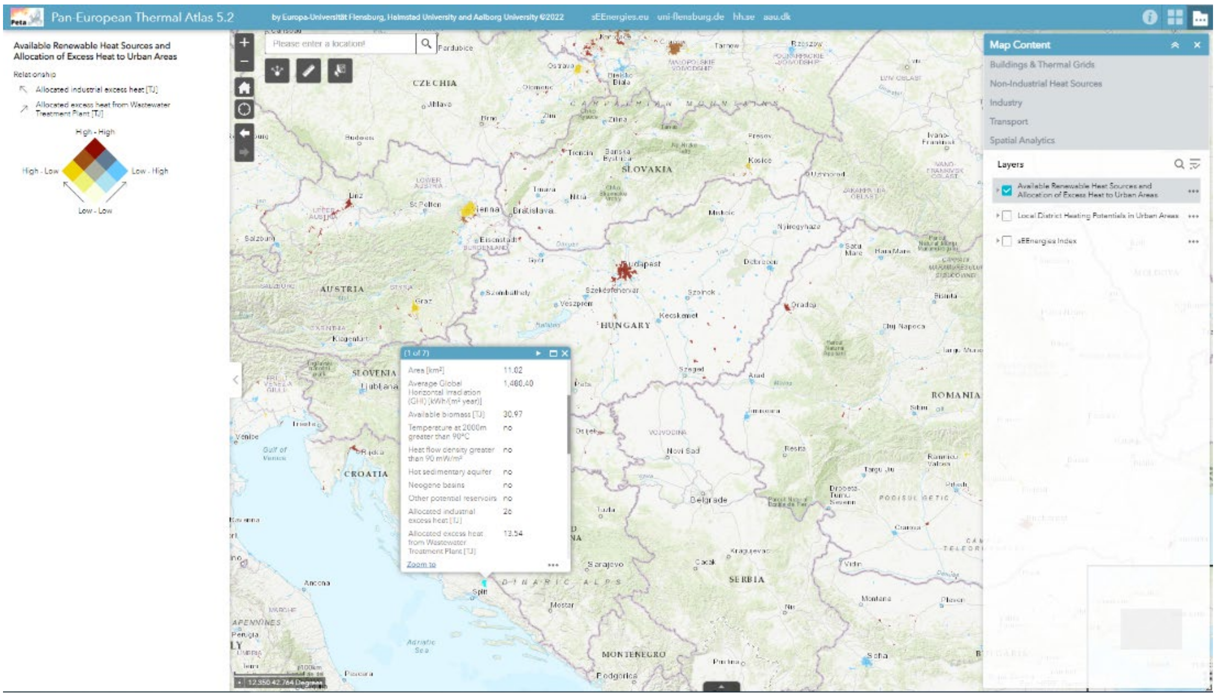

Figure 18. Screenshot of Peta 5.2 having activated the map layer which shows Urban Areas with allocated renewable and excess heat.

3.7. The sEEnergies Index

The inclusion of a multitude of synergetic energy efficiency measures in a geospatial representation of high geographical resolution for all of Europe is challenging.

First, many of the parameters used to describe energy efficiency do not use the same metric. While energy saving potentials in e.g. the built environment can be expressed as the percentage of heat demand that can be saved by means of insulation measures, efficiency potentials, and especially their drivers, may not always be described by ratios or energy units.

Second, because the system analyses of the sEEnergies project happen at the national levels, results would need to be disaggregated to local levels in order to achieve a geospatial representation at the desired scale. If the objective nevertheless is to achieve local studies of synergies between energy efficiency across sectors, these must rely on spatial representations of their drivers and some of the inputs to the system analyses.

Therefore, as many of the drivers of energy efficiency, such as the building mass and its specific heat demands, the properties of individual industrial processes, or the intra- and inter-city transport distances, have been mapped in a bottom-up manner, they can form the basis of a spatially distributed mapping of energy efficiency potentials. However, except in the heating sector, these cannot be mapped in energy terms, but must rely on mapping the drivers of these potentials. And a common framework has to be designed, which allows for the comparison of diverse metrics and units.

To address this, a common index has been developed, which values and weighs individual and map-able phenomena in a common overlay model, which relies on the Urban Areas as a geographical entity, see Table 8. For each of the three sectors buildings, industry and transport, key parameters have been determined. Each parameter, represented by a source map, is then translated into a value map by means of reclassification via a value table. The value maps are then arithmetically weighted to produce a composite map, as shown in Figure 19 below.

Table 8. Input parameters, grading method and weights as well as sEEnergies data used to generate an index for individual Urban Areas

Sector	Parameter	Grading	Weight	Layers used
Buildings	HD efficiency potential	manual	20%	HD, BL2050 & FE 2050
	Ability to develop DH	Jenks natural	10%	HDD >50 relative to HD BL2050
	Development of the built environment	geometric	10%	HD FE2050/HD 2015
Industry	National efficiency potentials by fuel demands	Jenks natural	15%	Industrial WP3 data
	Plant excess heat potential density	Jenks natural	15%	D5.2 Ind. excess heat
Transport	National EE potentials	Jenks natural	15%	WP2 TransportPlan
	Cycling potentials		15%	WP2 Cycling characterization

This method to assign composite weighted criteria is known from multi-criteria modelling and widely used in decision-making. Its major weakness, which is the often non-transparent, subjective valuing and weighting, must be reflected against its major strength, which is the ability to compare otherwise incomparable phenomena. While the synergies of energy efficiency on national levels can be quantified by means of systems analyses, on the local level this will not work. Instead, a semi-quantitative approach can be used, e.g. the effect of modal shift and the consequences on electricity consumption is only modelled on the national level; on the local level, merely the underlying geography of urban areas can be used to tell whether the area is more or less suitable for shifting to public transport, if at all. While synergies between modal shift and the generation of renewable energy can be modelled for a nation, this link is not visible nor is it subject to modelling on the local scale. However, for Urban Areas, the contributions from each index parameter can be visualised and retrieved in a semi-quantitative way.

The sEEnergies Index is modelled using UA data. These are derived from spatial analyses of energy efficiency in buildings, the potential for district heating, the allocation of heat sources, or the local availability of renewable heat sources. Point data, such as energy efficiency in industry, has been related to UA by means of density mapping, which establishes a quantification of magnitude and distance between industrial sites and the UA nearby. National results from the IndustryPLAN model have been used along with national TransportPLAN results. Both of these national data have been related to local conditions using individual plant and urban geography data.

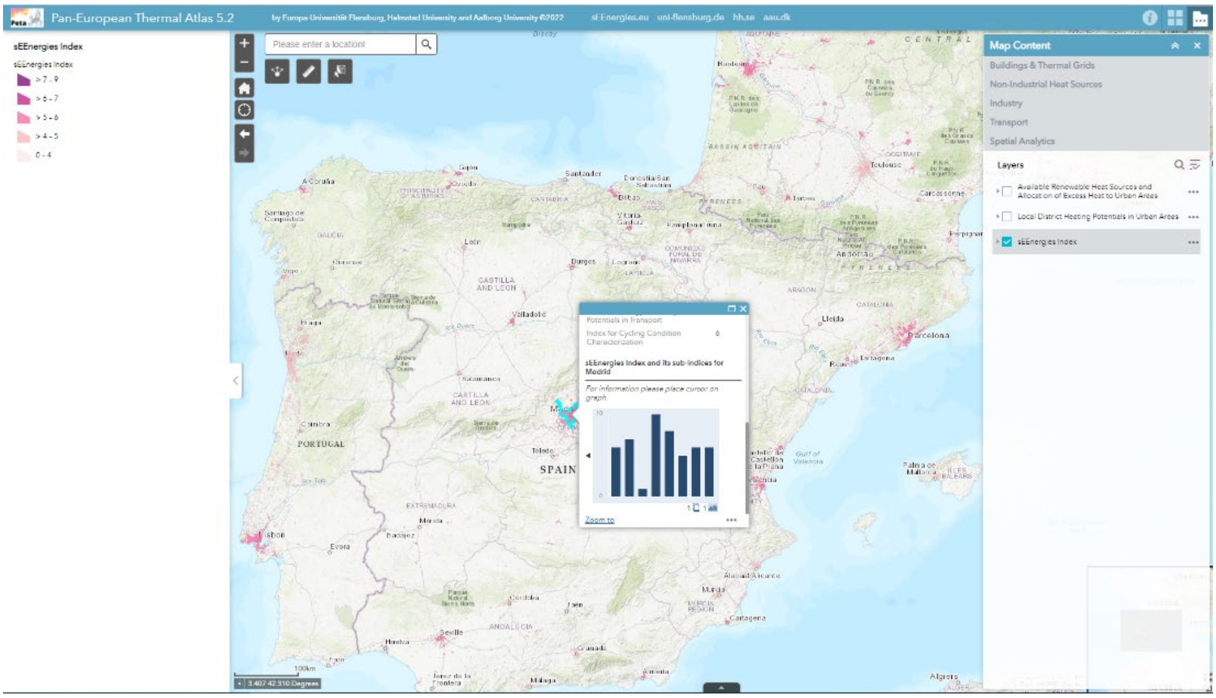

Figure 19. Screenshot of the sEEnergies Index layer within Peta 5.2.

As a composite metric, the sEEnergies Index serves as our conceptual mode to assess and present spatially evaluated energy efficiency potentials for EU27 plus the United Kingdom, and it may also be regarded as an output from the spatial analytics performed in work package 5 of the sEEnergies project. In terms of results, a total of 146,496 Urban Areas have been assigned an index value, which is presented in Table 9.

Table 9. Distribution and number of Urban Areas by population classes and according to assessed sEEnergies Index, for EU27+UK

	sEEnergies Index										
Population classes	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**Grand Total**
< 1 000			1,266	18,977	55,545	28,317	2,645	94			**106,844**
1 000 - <10 000			212	4,547	15,419	12,312	1,800	67			**34,357**
10 000 - <100 000			2	284	1,431	2,122	872	33			**4,744**
100 000 - < 1 000 000				10	126	257	123	4	1		**521**
>= 1 000 000					5	13	11	1			**30**
Grand Total			1,480	23,818	72,526	43,021	5,451	199	1		**146,496**

It can be seen from Table 9 that with the applied valuing scheme, the majority of urban areas is featuring median values slightly above "5", which is due to the valuing by the methods used. Therefore, the index shows whether urban areas have a higher or lower energy efficiency potential in all sectors above or below most other urban areas.

It is also visible that larger urban areas have slightly higher scores in the efficiency index, which is caused by higher potentials to save heat in buildings, and by better possibilities to develop district heating. A closer look at how the sub-index values score for each area will reveal that larger urban areas have challenges in the use of renewable energy sources, and in the transportation sector.

A national comparison of index values, see Table 12 in the appendix, reveals that each country has different opportunities to increase energy efficiency. Some countries like Germany, Ireland and Slovakia have higher potentials for energy efficiency, while in Denmark, Finland and Sweden, the score is low due to the many efficiency measures already implemented. Also, many countries like Hungary, the Netherlands, or Portugal have lower indices, suggesting shortcomings in other areas.

The sEEnergies index needs to be further developed once the weighting and valuing of criteria have been understood better. A potential case of application is the translation of national results from the energy systems analysis performed in WP6 to local conditions. If e.g. it turns out that electromobility is synergetic with local power system balancing by means of advanced district heating, then the index can be used to establish this synergetic relationship in a semi-quantitative manner. Vice versa, the index can be adjusted to show the sensitivity of the measures proposed on national and European levels to local conditions. If, for example the operation of a ”Smart Energy System” (H. Lund, Østergaard, Connolly, & Mathiesen, 2017) in an area is very reliant on local conditions, like the presence of heat markets, excess heat activities, or available renewable energy sources, then the likelihood of being able to establish such systems can be verified using local energy sector data. Finally, the sEEnergies Index can be applied for the dissemination of project results, e.g. when local conditions need to be verified and visualised.

4. Dissemination and sharing

Besides for analytical purposes, the map layers and the Pan-European Thermal Atlas (Peta 5.2) have been prepared to facilitate the dissemination and sharing of geospatial data and information at high levels of detail and for all of the EU.

4.1. Pan-European Thermal Atlas (Peta 5.2)

The web mapping application Pan-European Thermal Atlas 5 (Peta 5) was developed and documented in two main steps during the sEEnergies project. In the first step the web mapping application itself and its first set of layers were provided (see the D5.3 deliverable report (Möller et al., 2020)). In the second step (see the D5.5 deliverable report (Wiechers et al., 2022)), the application was complemented with layers based on sector-specific future scenario data which were finalised after the first launch of Peta 5.

As all the screenshots from Peta 5.2, included in this report, has illustrated, the Peta disseminates research findings which are of geographical nature. The online map can be used to get a better understanding of the geography of energy efficiency and the synergies across sectoral divides for given locations. By assembling data from several sectors and phenomena, the online map generally supports comparisons and first-order assessments of local, regional, and national, level energy efficiency potentials for the current EU member states plus the United Kingdom.

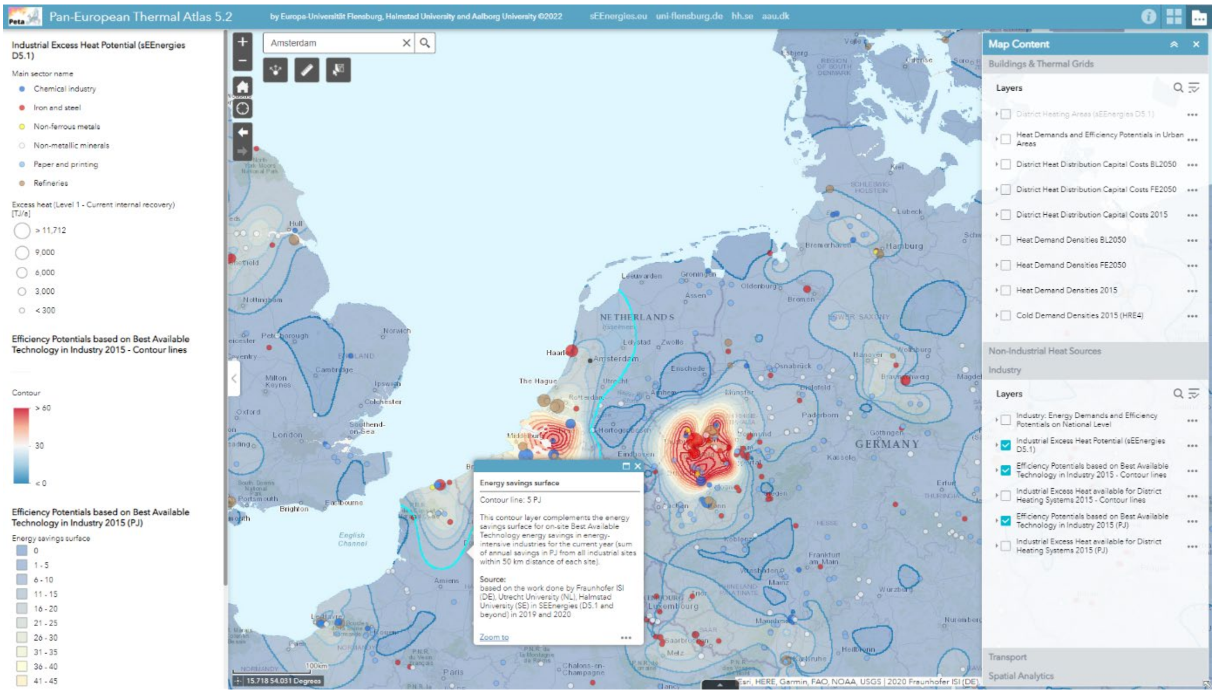

Figure 20. Screenshot from Peta 5.2 illustrating map layers related to energy efficiency potentials in the industry sector, in this case an energy efficiency surface layer, based on contour lines, that delineate total energy saving potentials within 50-km distances of existing industrial sites possible by introducing on-site Best Available Technologies (BAT).

Figure 20 provides yet one more example screenshot from Peta 5.2. On the right-hand side in this figure may be seen the typical layer groups and their respective individual layers, which can be accessed by a click on the folder symbol in the upper right corner. The panel on the left-hand side contains the legends of the selected active layers. Descriptive data contained in the layer is provided by pop-ups, which can be opened with a click on a layer element like a point, a line, or a polygon. Moreover, users can search places and measure distances. Elements of the atlas can be selected and exported in tabular format, and map views can be shared via links and in social media.

Peta 5.2 is referenced as (Peta 5.2, 2022) and can be accessed via the following URL: https://tinyurl.com/peta5seenergies.

4.2. sEEnergies Open Data Hub

The online data sharing platform "sEEnergies Open Data Hub" provides information about and download options for several geospatial datasets which are included in the Peta 5.2 or have been part of Peta 5.1. The sEEnergies Open Data Hub consist of a scrollable front page with a search function (see Figure 21). It also gives an overview of the eight categories into which the provided datasets are grouped (see Figure 22).

Figure 21. Screenshot of the sEEnergies Open Data Hub front page.

First of all, the datasets on the sEEnergies Open Data Hub are categorized by sector (Buildings, Industry and Transport) or by grid type (Gas or Thermal Grids). This approach follows the structure of the sEEnergies project.

In addition, there are two categories which refer to particular deliverables (D5.1 (Fleiter et al., 2020) and D5.2 (Wiechers et al., 2020)), and one category for the sEEnergies Index. The datasets of these three categories are interlinked with the datasets of more than one sector and grid category.

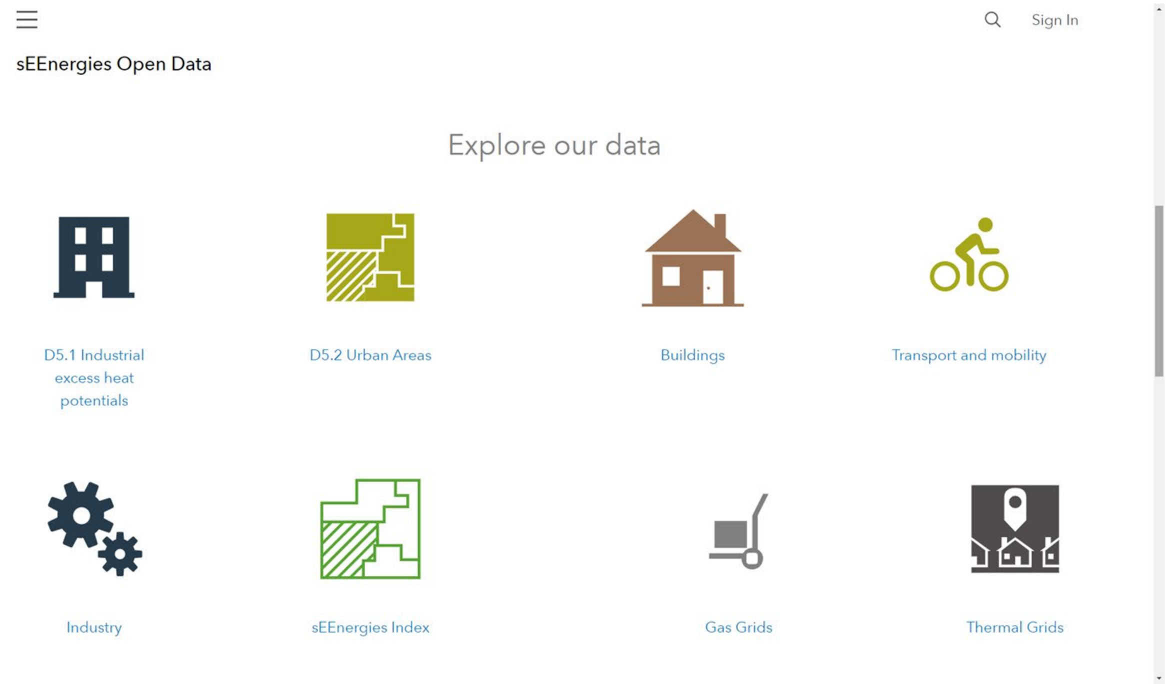

Figure 22. Screenshot of the category overview at the sEEnergies Open Data Hub.

Where possible, the geospatial datasets are published under the Creative Commons (CC) BY 4.0 licence. Raster data can be downloaded as tiff-files, while other geospatial datasets can be downloaded in several different file formats, for example as Shapefiles (.shp), Comma-Separated Values files (.csv), Keyhole Markup Language files (.kml), and GeoJSON-files (.geojson).

The download capabilities at the Open Data Hub are illustrated in Figure 23, with an example referring to the D5.2-associated Urban Areas Demographical attributes-dataset (Wiechers et al., 2020).

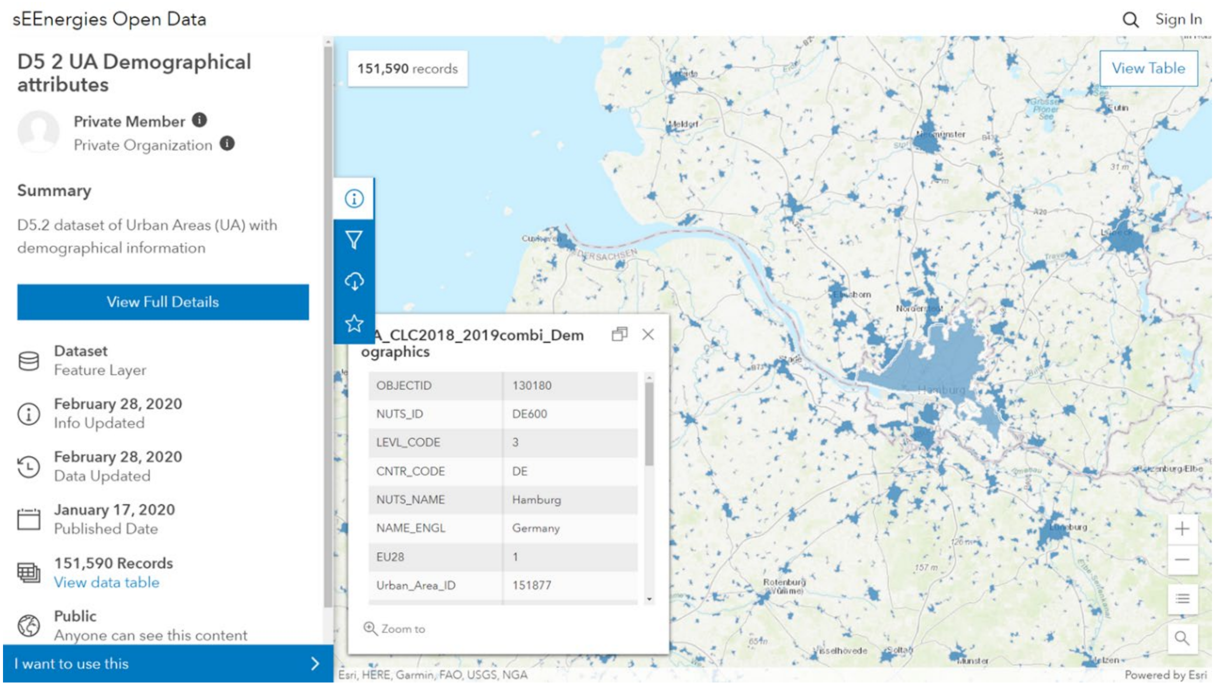

Figure 23. Screenshot of the download page for the D5.2 Urban Areas Demographical attributes-dataset at the sEEnergies Open Data Hub.

Noteworthy, there is an interlinkage between the Open Data Hub and the web mapping applications developed by work package 5 in the sEEnergies project. As illustrated in Figure 24, three web mapping applications can be access directly from the Open Data Hub: Most importantly Peta 5.2, but also the D5.1 and the D5.2 Dataset Web-App.

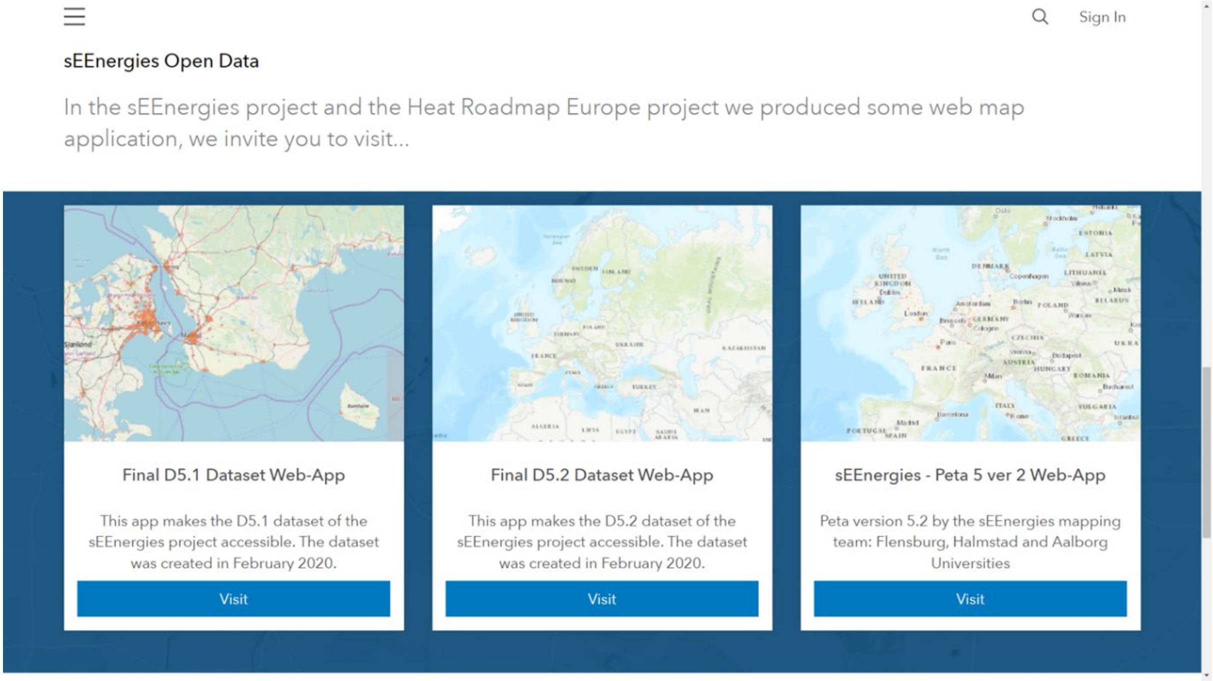

Figure 24. Screenshot of links to the various online mapping apps at the sEEnergies Open Data Hub, for example to Peta 5.2.

The sEEnergies Open Data Hub is referenced as (sEEnergies Open Data Hub, 2020) and can be accessed via the following URL: https://s-eenergies-open-data-euf.hub.arcgis.com/

4.3. Story Maps

In cooperation with the sEEnergies project partners who worked on the Energy Efficiency Potentials (work package 1 – 3), Story Map have been developed. They are now interactive online tools which allow users to visualize and understand the impact of energy efficiency measures in the countries of the EU27+UK, on different geographical levels.

From the Story Map Collection (shown as a screenshot in Figure 25 below), three sector-specific Story Maps have been prepared:

- Future Heat Demand, Efficiency Potentials and Supply in residential and service-sector Buildings
- Transport Sector Energy Efficiency Potentials
- Industrial Energy Efficiency Potentials

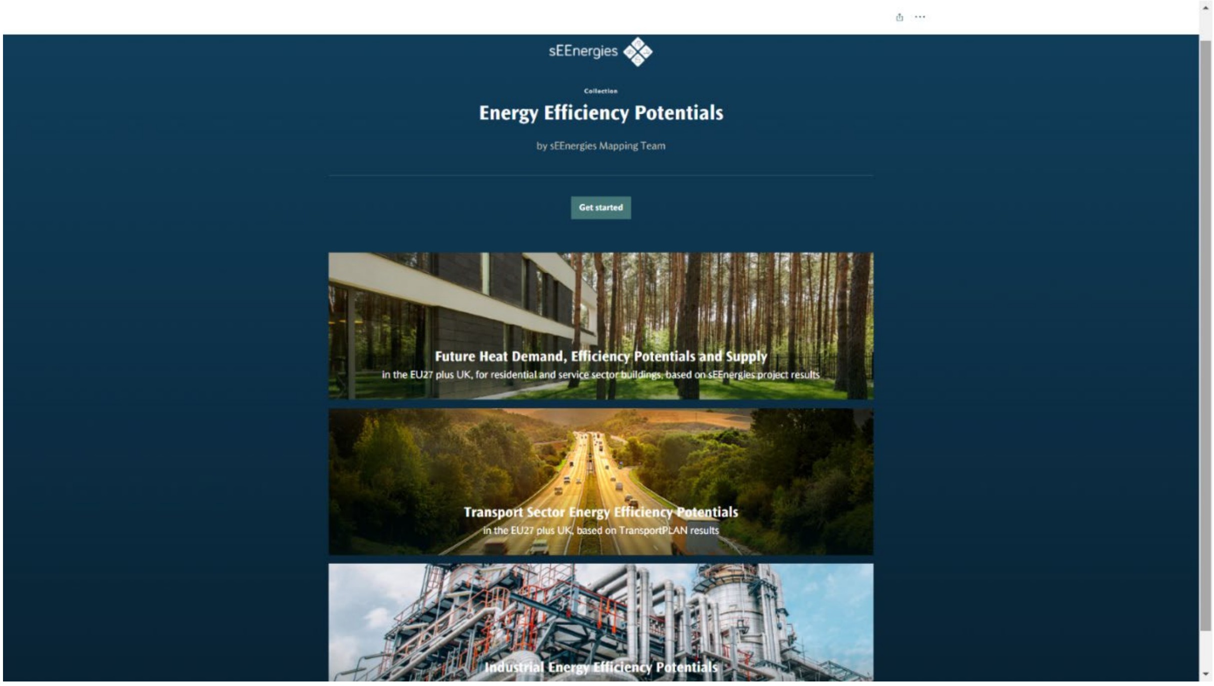

Figure 25. Screenshot of the sEEnergies Story Map Collection page. Three separate Story Maps are included in the current collection of Energy Efficiency Potentials: 1. Future Heat Demand, Efficiency Potentials and Supply; 2. Transport Sector Energy Efficiency Potentials; and 3. Industrial Energy Efficiency Potentials.

The Story maps of the sEEnergies project are referenced (sEEnergies mapping team, 2022) and can be accessed via the following URL: https://tinyurl.com/sEEnergiesStorymaps.

5. Conclusions / Outlook

Energy efficiency is largely determined by the local conditions in the built environment, in the transport sector, and in industry. Synergetic effects between these sectors depend on their geospatial relationship. The objective of the present report is to account for the spatial models of energy efficiency and the geospatial analysis needed to quantify and locate energy efficiency potentials across sectors in all of Europe.

In buildings, future heat demands on the national level are being distributed by age class of built-up areas and using innovative models of future population distribution. The capital costs of district heat distribution, combined with the density of heat demands, allow for the assessment of the economic potentials of future district heating. In the transport and industrial sectors, energy efficiency potentials have been associated to locations, and transmission infrastructures have been mapped. In combining all these aspects, spatial analytics have helped improving the understanding of opportunities and constraints that arise from the geography of energy systems.

Energy efficiency potentials have been mapped at different scales, from local to national. Cost curves for district heating in the member states help establishing the economic potential of district heating. For the energy systems analysis in work package 6 of the present sEEnergies project, a national matrix has been developed that relates energy efficiency in buildings and district heating potentials. For the conversion of natural gas to district heating, areas of interest can be mapped, which will allow for combining present gas use with infrastructural aspects. For almost 150,000 settlements, local potentials of district heating have been quantified, and associated to potential heat sources from industrial and wastewater treatment plants, as well as locally available renewable energy sources.

Finally, the sEEnergies Index shows local potentials for improving energy efficiency and utilising synergies in all settlements of the EU27 plus the UK. It can be used to visualise and compare energy efficiency across sectors, technologies, and countries. Overall, the report documents how dissemination can be facilitated using the online geospatial information and mapping applications prepared in the sEEnergies project.

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7. Appendix

7.1. DHDCC post-processing to establish average distribution and service pipe costs

The calculation of the average distribution and service pipe cost at a certain marginal cost is slightly more complicated; it entails determining the heat weighted average cost for building distribution or service pipes in those cells that have a cost equal to the marginal cost under consideration. It can be illustrated by the following function:

$$(Average\ distribution/service\ cost)_{marginal\ cost=Cd_i} = \frac{\sum_{j=1}^{N} Q_j \cdot P_j \cdot \alpha_j}{\sum_{j=1}^{N} Q_j}$$

Where:

$(Average\ distribution/service\ cost)_{marginal\ cost=Cd_i}$ is the mean cost of distribution/service pipes in those areas which have a marginal cost equal to Cd_i.

Q_j is the amount of heat in the cell j.

P_j is the annualised specific investment cost for distribution or service pipes.

α_j is a decision variable with a value of 1 if the cell j has a marginal capital cost equal to Cd_i or zero otherwise.

N is the number of hectare cells in the geographic area under analysis.

7.2. DHDCC tabular output attributes

Table 10. List of tabular output attributes (columns) generated in post-processing of DHDCC model outputs

Column headers	Description
country_code	Two-letter country code, always written in capital letters, and often used as an abbreviation in statistical analyses, tables, figures or maps. The protocol order in which countries are listed is based on the alphabetical list of countries in their national language for EU Member States.
marginal_cost_E_GJ	Annualised specific capital cost of distribution and service pipes (€/GJ)
heat_demand_at_cost_level_GJ	Heat demand in a given region that can be supplied at the marginal cost under consideration (GJ)
cumulative_heat_demand_GJ	Heat demand in a given region that can be supplied at a cost equal or below to the marginal cost under consideration (GJ)
cumulative_heat_demand_proportion	Proportion of a region's total heat demand that can be supplied at a cost equal or below to the marginal cost under consideration (-)
cumulative_heat_demand_percentage	Proportion of a region's total heat demand that can be supplied at a cost equal or below to the marginal cost under consideration (%)
average_cost_E_GJ	Mean annualised specific capital cost in areas with a marginal cost equal or below to the marginal cost under consideration. Ratio between the annualised cumulative investment and the cumulative heat demand (€/GJ)
investment_at_cost_level_E	Necessary investment to supply heat in those areas with a marginal cost equal to the marginal cost under consideration. Product of the marginal cost and the heat demand that can be supplied at the marginal cost under consideration (€)
cumulative_investment_E	Necessary investment to supply heat in areas with a marginal cost equal or below to the marginal cost under consideration (€)
area_at_cost_level_ha	Ground area with a marginal cost equal to the marginal cost under consideration (ha)
average_distribution_cost_at_total_cost_level_E_GJ	Ratio between the annualised investment for distribution pipes and the heat demand in the areas which have the marginal cost under consideration (€/GJ)
average_service_cost_at_total_cost_level_E_GJ	Ratio between the annualised investment for service pipes and the heat demand in the areas which have the marginal cost under consideration (€/GJ)
proportion_cost_distribution	Proportion of the cost of the distribution pipes with respect to the sum of distribution and service pipes (-)
proportion_cost_service	Proportion of the cost of the service pipes with respect to the sum of distribution and service pipes (-)
investment_distribution_at_cost_level_E	Investment for distribution pipes in the areas which have the marginal cost under consideration (€/GJ)
investment_service_at_cost_level_E	Investment for service pipes in the areas which have the marginal cost under consideration (€/GJ)
cumulative_investment_distribution_E	Investment for distribution pipes in the areas which have a marginal cost equal or below to the marginal cost under consideration (€/GJ)
cumulative_investment_service_E	Investment for service pipes in the areas which have a marginal cost equal or below to the marginal cost under consideration (€/GJ)

7.3. DHDCC model outputs for 50% future district heating heat market shares

Table 11. District heating network investment costs for the EU27 member states (MS) plus the United Kingdom (UK) under the sEEnergies 2050 scenarios (Baseline (BL2050) and frozen efficiency (FE2050)), at anticipated 50% national heat market shares for district heating

MS	Marginal cost [€/GJ]		Average cost [€/GJ]		Acc. heat demand [PJ/a]		Total investment [M€]	
Scenario	**BL2050**	**FE2050**	**BL2050**	**FE2050**	**BL2050**	**FE2050**	**BL2050**	**FE2050**
AT	26.59	21.15	9.29	7.32	88.5	112.5	16,113	16,136
BE	18.35	14.3	8.58	6.16	129.9	172.8	21,848	20,848
BG	10.02	8.56	5.16	4.42	47.3	53.8	4,780	4,661
CY	110.18	81.96	52.81	39.97	2.7	3.7	2,751	2,918
CZ	15.19	11.49	7.01	5.26	94.7	121.7	13,018	12,545
DE	18.26	12.23	9.06	5.99	813.8	1138.8	144,498	133,669
DK	14.79	13.62	7.79	6.96	95.1	111.6	14,527	15,218
EE	5.08	3.88	2.43	1.90	17.8	24.1	850	896
EL	22.77	21.69	10.26	9.65	45.5	47.5	9,155	8,984
ES	9.21	8.03	4.64	4.06	389.2	447.0	35,390	35,531
FI	10.05	8.23	4.63	3.55	89.7	105.1	8,144	7,315
FR	18.12	14.11	7.64	5.95	559.4	740.1	83,801	86,293
HR	6.39	3.77	4.39	2.70	19.3	46.6	1,662	2,463
HU	21.82	13.62	9.38	5.93	79.7	109.5	14,652	12,731
IE	35.12	24.73	22.32	11.90	28.1	46.5	12,314	10,840
IT	11.12	9.08	5.67	4.58	561.0	670.8	62,289	60,176
LT	10.06	6.99	5.17	3.20	22.9	50.1	2,326	3,140
LU	12.49	6.38	6.26	3.23	9.7	21.3	1,192	1,347
LV	4.38	3.31	2.08	1.57	28.0	37.4	1,143	1,147
MT	13.41	11.44	6.30	5.02	1.9	2.2	232	216
NL	19.93	16.16	12.19	9.49	168.2	212.7	40,169	39,550
PL	15.63	12.01	6.82	5.20	222.2	324.3	29,727	33,036
PT	50.98	45.7	20.46	18.49	31.5	35.6	12,626	12,895
RO	34.68	27.49	16.22	11.52	71.8	95.0	22,827	21,448
SE	18.59	15.58	7.76	5.89	120.8	146.2	18,369	16,886
SI	6.48	3.65	4.56	2.49	15.1	34.8	1,344	1,694
SK	24.16	10.47	14.03	5.88	28.8	85.1	7,908	9,812
UK	15.8	12.1	9.10	6.44	549.7	715.4	98,062	90,278
Max. value	**110.18**	**81.96**	**52.81**	**39.97**	**813.8**	**1138.8**	**144,498**	**133,669**
Min. value	**4.38**	**3.31**	**2.08**	**1.57**	**1.9**	**2.2**	**232**	**216**
Avg. value	**20.70**	**15.78**	**10.07**	**7.31**	**154.7**	**204.0**	**24,347**	**23,667**

7.4. DHDCC BL2050 and FE2050 cost curves in units [€/GJ] and [€/MWh]

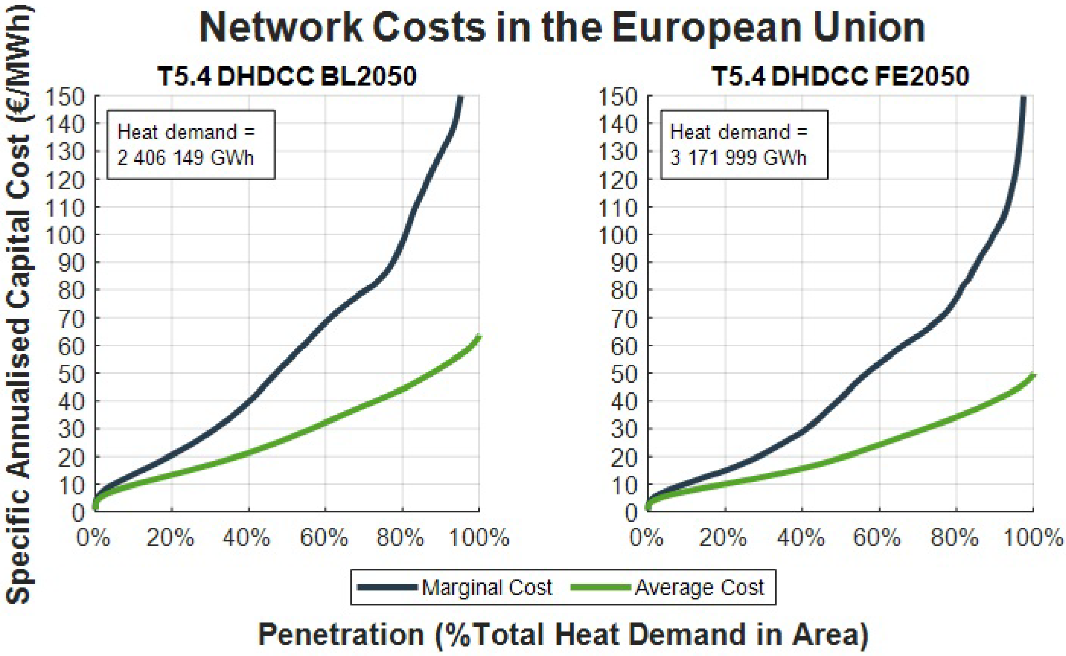

Figure 26. Grand total marginal and average distribution capital cost levels and the corresponding district heat market shares in the 27 EU Member States plus United Kingdom for BL2050 (left) and FE2050 (right) [€/MWh]. Cost levels reflect costs for both distribution and service pipes.

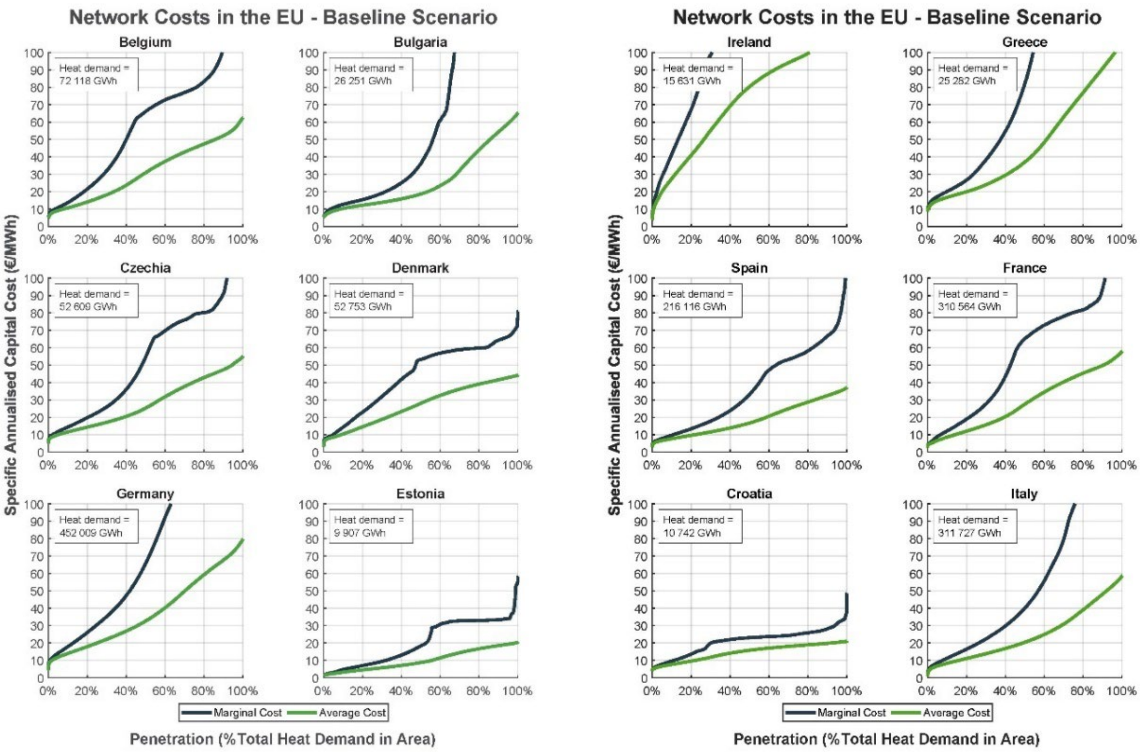

Figure 27. BL2050 cost curves for BE, BG, CZ, DK, DE, EE (left) and IE, EL, ES, FR, HR, IT (right) [€/MWh].

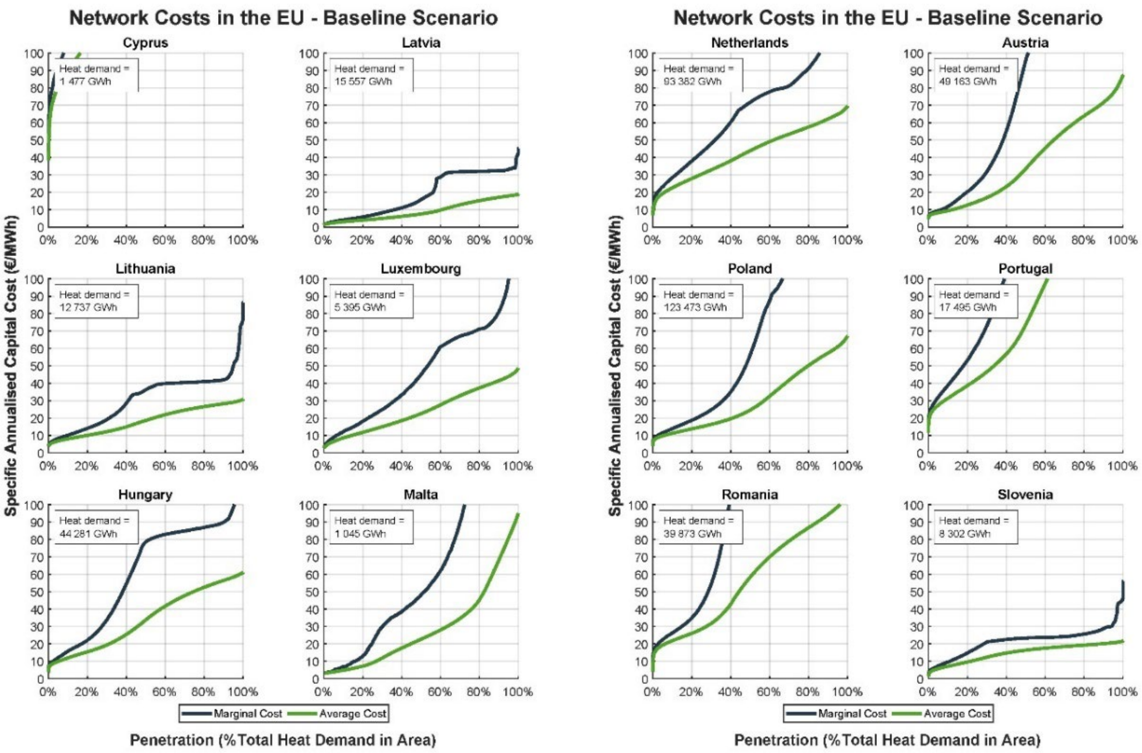

Figure 28. BL2050 cost curves for CY, LV, LT, LU, HU, MT (left) and NL, AT, PL, PT, RO, SI (right) [€/MWh].

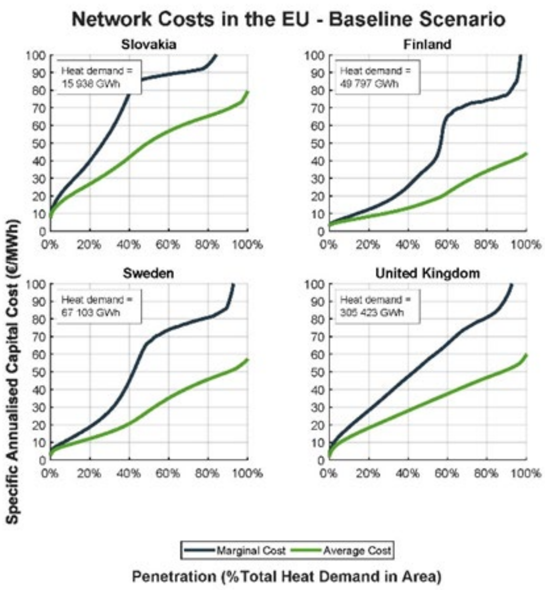

Figure 29. BL2050 cost curves for SK, FI, SE, UK [€/MWh].

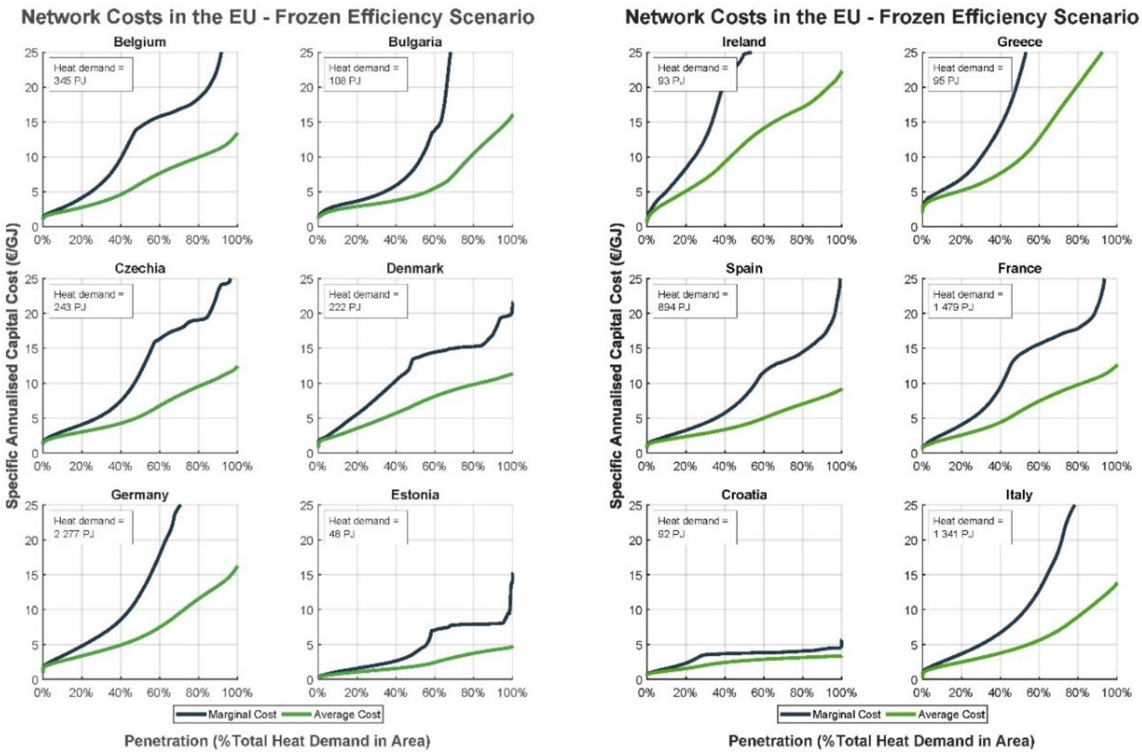

Figure 30. FE2050 cost curves for BE, BG, CZ, DK, DE, EE (left) and IE, EL, ES, FR, HR, IT (right) [€/GJ].

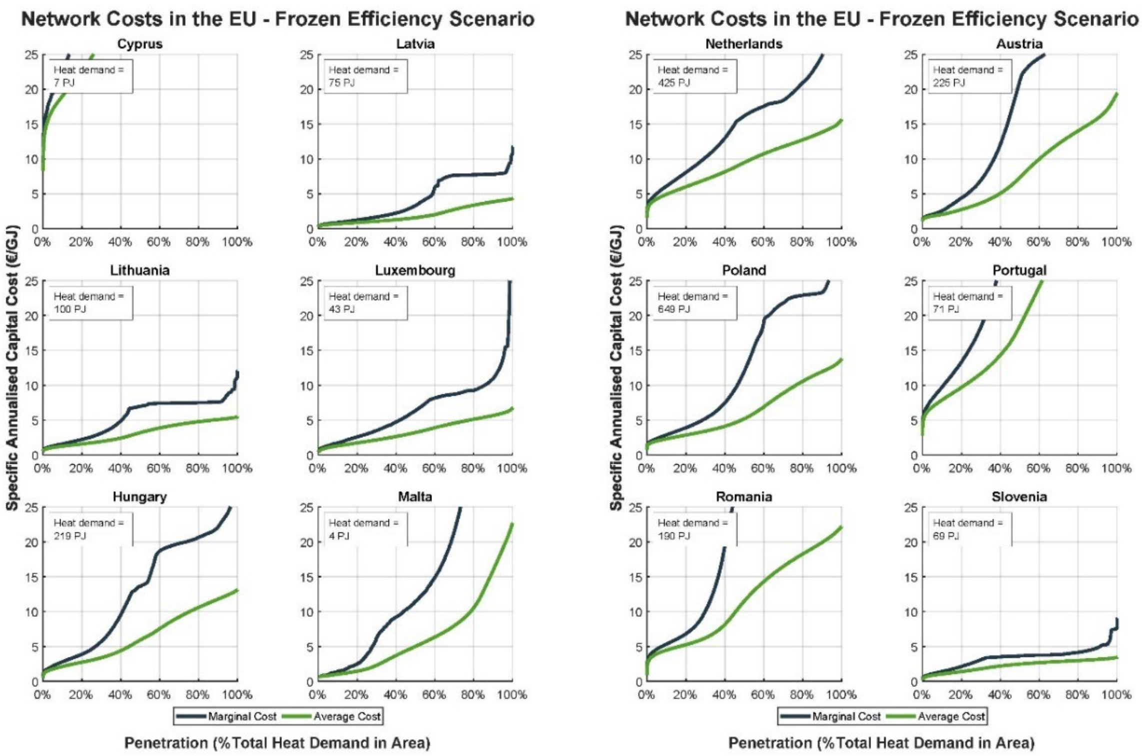

Figure 31. FE2050 cost curves for CY, LV, LT, LU, HU, MT (left) and NL, AT, PL, PT, RO, SI (right) [€/GJ].

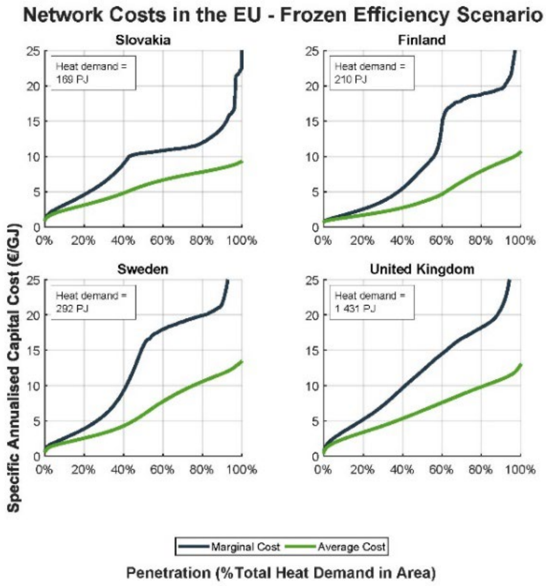

Figure 32. FE2050 cost curves for SK, FI, SE, UK [€/GJ].

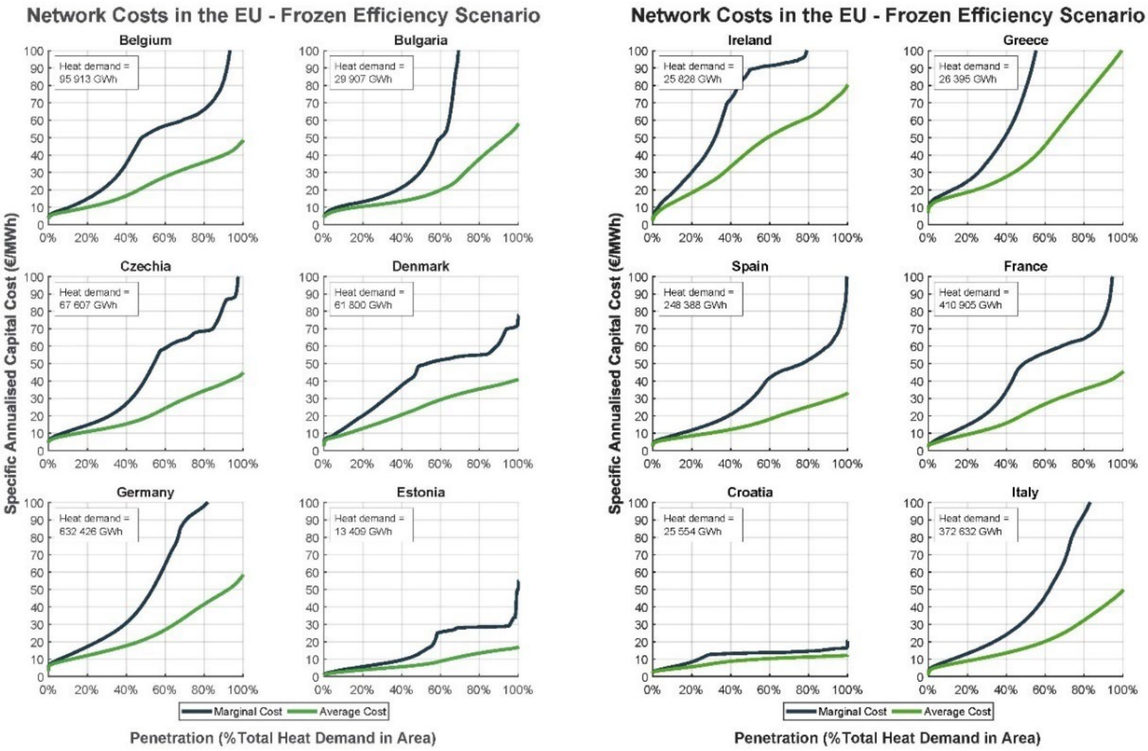

Figure 33. FE2050 cost curves for BE, BG, CZ, DK, DE, EE (left) and IE, EL, ES, FR, HR, IT (right) [€/MWh].

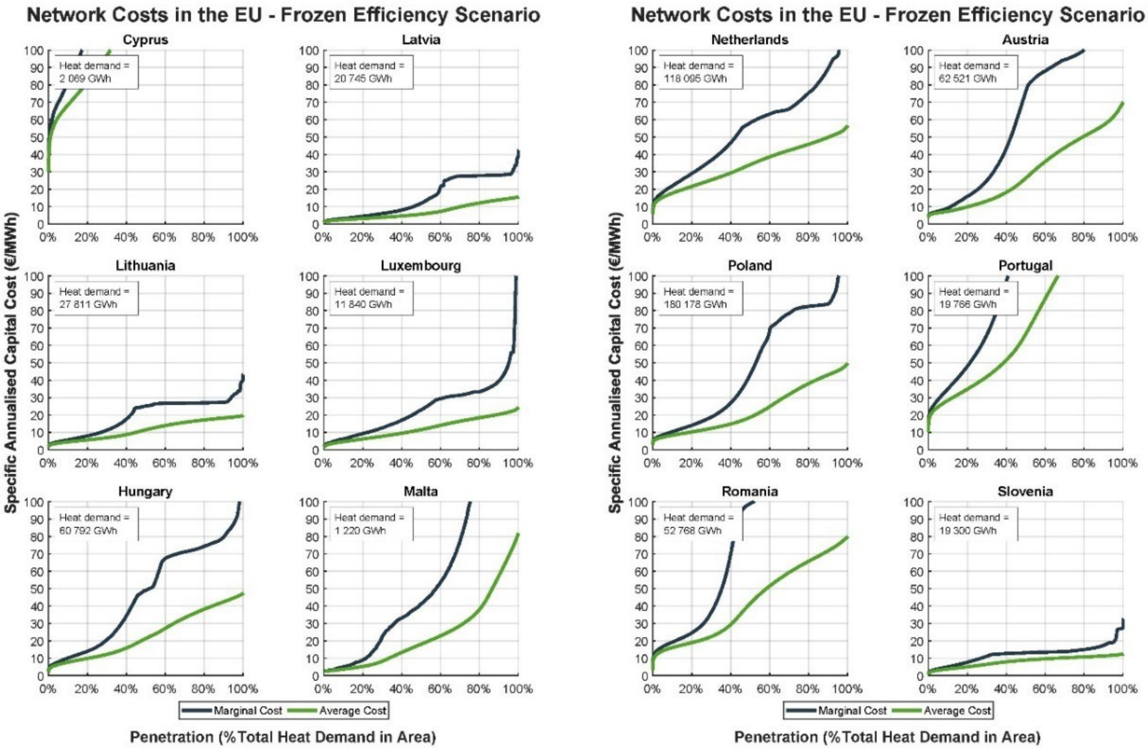

Figure 34. FE2050 cost curves for CY, LV, LT, LU, HU, MT (left) and NL, AT, PL, PT, RO, SI (right) [€/MWh].

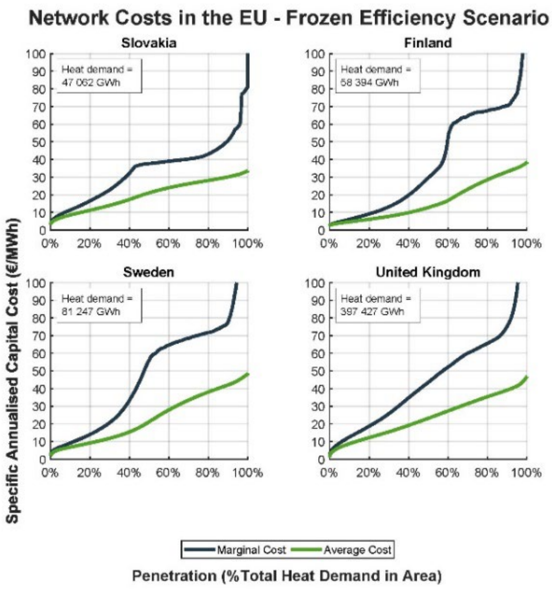

Figure 35. FE2050 cost curves for SK, FI, SE, UK [€/MWh].

7.5. The sEEnergies Index for EU27 member states and the United Kingdom

Table 12. Distribution and number of Urban Areas by population classes and according to assessed sEEnergies Index, for the EU27 member states plus the United Kingdom

	sEEnergies Index										
Population classes	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**Grand Total**
AT			214	1,728	1,652	314	4				**3,912**
< 1 000			185	1,466	1,280	157					**3,088**
1 000 - <10 000			29	256	341	131					**757**
10 000 - <100 000				6	29	23	3				**61**
100 000 - < 1 000 000					2	3					**5**
>= 1 000 000							1				**1**
BE			236	779	1,746	114					**2,875**
< 1 000			225	674	1,263	36					**2,198**
1 000 - <10 000			11	101	419	29					**560**
10 000 - <100 000				4	57	37					**98**
100 000 - < 1 000 000					6	12					**18**
>= 1 000 000					1						**1**
BG				2,072	1,806	92					**3,970**
< 1 000				1,818	1,363	22					**3,203**
1 000 - <10 000				251	396	47					**694**
10 000 - <100 000				3	44	19					**66**
100 000 - < 1 000 000					2	4					**6**
>= 1 000 000					1						**1**
CY				1	155	131	5				**292**
< 1 000				1	134	101	2				**238**
1 000 - <10 000					20	28	2				**50**
10 000 - <100 000					1	1					**2**
100 000 - < 1 000 000						1	1				**2**
CZ				478	3,528	1,860	113	4			**5,983**
< 1 000				460	3,127	1,255	47	3			**4,892**
1 000 - <10 000				18	390	527	31				**966**
10 000 - <100 000					10	75	33	1			**119**
100 000 - < 1 000 000					1	2	2				**5**
>= 1 000 000						1					**1**
DE			2	872	11,179	9,628	1,081	7			**22,769**
< 1 000			2	750	8,377	5,324	168				**14,621**
1 000 - <10 000				122	2,734	3,799	464				**7,119**
10 000 - <100 000					67	480	393	6			**946**
100 000 - < 1 000 000					1	24	54	1			**80**
>= 1 000 000						1	2				**3**
DK			9	1,196	315	8					**1,528**
< 1 000			9	873	150						**1,032**
1 000 - <10 000				307	124						**431**
10 000 - <100 000				16	36	7					**59**

100 000 - < 1 000 000					5	1					**6**
EE				46	533	42	1				**622**
< 1 000				45	475	20	1				**541**
1 000 - <10 000				1	53	12					**66**
10 000 - <100 000					5	8					**13**
100 000 - < 1 000 000						2					**2**
EL				1,348	1,837	200	10				**3,395**
< 1 000				1,205	1,479	116	1				**2,801**
1 000 - <10 000				137	317	61					**515**
10 000 - <100 000				6	41	19	1				**67**
100 000 - < 1 000 000						4	7				**11**
>= 1 000 000							1				**1**
ES			150	3,798	3,045	215					**7,208**
< 1 000			146	2,793	1,611	55					**4,605**
1 000 - <10 000			4	902	1,151	78					**2,135**
10 000 - <100 000				99	262	57					**418**
100 000 - < 1 000 000				4	21	22					**47**
>= 1 000 000						3					**3**
FI			375	1,064	196	17					**1,652**
< 1 000			337	857	110	6					**1,310**
1 000 - <10 000			38	197	56	3					**294**
10 000 - <100 000				10	25	7					**42**
100 000 - < 1 000 000					4	1					**5**
>= 1 000 000					1						**1**
FR				2,320	16,448	7,345	103				**26,216**
< 1 000				2,059	13,581	5,410	23				**21,073**
1 000 - <10 000				255	2,729	1,672	27				**4,683**
10 000 - <100 000				6	121	231	43				**401**
100 000 - < 1 000 000					17	31	5				**53**
>= 1 000 000						1	5				**6**
HR					125	1,002	597	1			**1,725**
< 1 000					106	795	458				**1,359**
1 000 - <10 000					17	195	115				**327**
10 000 - <100 000					2	12	21	1			**36**
100 000 - < 1 000 000							3				**3**
HU			13	1,753	1,686	215	12				**3,679**
< 1 000			12	1,318	1,040	95	8				**2,473**
1 000 - <10 000			1	433	574	68					**1,076**
10 000 - <100 000				2	68	50	3				**123**
100 000 - < 1 000 000					4	2					**6**
>= 1 000 000							1				**1**
IE				13	469	256	61	1			**800**
< 1 000				13	382	154	23	1			**573**
1 000 - <10 000					83	80	22				**185**
10 000 - <100 000					4	22	14				**40**

100 000 - < 1 000 000							1				**1**
>= 1 000 000							1				**1**
IT				954	5,418	3,710	485				**10,567**
< 1 000				766	3,246	1,548	149				**5,709**
1 000 - <10 000				187	2,010	1,764	226				**4,187**
10 000 - <100 000				1	157	362	105				**625**
100 000 - < 1 000 000					5	32	5				**42**
>= 1 000 000						4					**4**
LT					1,664	299	1				**1,964**
< 1 000					1,546	246					**1,792**
1 000 - <10 000					107	32					**139**
10 000 - <100 000					11	16	1				**28**
100 000 - < 1 000 000						5					**5**
LU				18	92	132	16				**258**
< 1 000				17	85	95	7				**204**
1 000 - <10 000				1	7	35	6				**49**
10 000 - <100 000						2	2				**4**
100 000 - < 1 000 000							1				**1**
LV				2	750	153	3				**908**
< 1 000				2	656	114	1				**773**
1 000 - <10 000					90	20	1				**111**
10 000 - <100 000					4	17	1				**22**
100 000 - < 1 000 000						2					**2**
MT			19	15							**34**
< 1 000			8	4							**12**
1 000 - <10 000			9	5							**14**
10 000 - <100 000			2	5							**7**
100 000 - < 1 000 000				1							**1**
NL			256	766	493	19					**1,534**
< 1 000			155	296	55						**506**
1 000 - <10 000			101	393	306	4					**804**
10 000 - <100 000				72	113	9					**194**
100 000 - < 1 000 000				5	19	6					**30**
PL				167	9,533	8,045	385	1			**18,131**
< 1 000				141	8,622	6,640	141				**15,544**
1 000 - <10 000				25	866	1,134	154				**2,179**
10 000 - <100 000				1	44	250	74	1			**370**
100 000 - < 1 000 000					1	20	16				**37**
>= 1 000 000						1					**1**
PT			108	1,322	931	14					**2,375**
< 1 000			93	1,002	676	7					**1,778**
1 000 - <10 000			15	297	209						**521**
10 000 - <100 000				23	43	3					**69**
100 000 - < 1 000 000					2	3					**5**
>= 1 000 000					1	1					**2**

RO				1	4,002	6,409	614	7			**11,033**
< 1 000				1	3,424	4,681	317	2			**8,425**
1 000 - <10 000					570	1,639	225	1			**2,435**
10 000 - <100 000					8	84	61				**153**
100 000 - < 1 000 000						5	11	3			**19**
>= 1 000 000								1			**1**
SE			66	1,372	1,352	135	7				**2,932**
< 1 000			65	1,179	931	59	4				**2,238**
1 000 - <10 000			1	190	352	33	1				**577**
10 000 - <100 000				3	65	40	1				**109**
100 000 - < 1 000 000					3	3	1				**7**
>= 1 000 000					1						**1**
SI					236	345	4				**585**
< 1 000					195	226	2				**423**
1 000 - <10 000					39	105					**144**
10 000 - <100 000					2	13	2				**17**
100 000 - < 1 000 000						1					**1**
SK					2	854	1,799	177	1		**2,833**
< 1 000					1	690	1,253	87			**2,031**
1 000 - <10 000					1	160	506	66			**733**
10 000 - <100 000						4	40	24			**68**
100 000 - < 1 000 000									1		**1**
UK			32	1,733	3,333	1,467	150	1			**6,716**
< 1 000			29	1,237	1,630	465	40	1			**3,402**
1 000 - <10 000			3	469	1,458	656	20				**2,606**
10 000 - <100 000				27	212	274	74				**587**
100 000 - < 1 000 000					33	71	16				**120**
>= 1 000 000						1					**1**
Grand Total			**1,480**	**23,818**	**72,526**	**43,021**	**5,451**	**199**	**1**		**146,496**

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