H/C outlook 2050 of cities with cross-city synthesis

Deliverable D2.6

TITLE
H/C outlook 2050 of cities with cross-city synthesis
Deliverable D2.6 (Edited version)

AUTHORS
Prepared by Urban Persson, Mohammad Saeid Atabaki, Luis Sánchez-García (School of Business, Innovation and Sustainability, Halmstad University, SE), and Peter Lichtenwöhrer (City of Vienna, Municipal Department 20 – Energy Planning, AT)

Reviewed by Viktoria Forstinger at Urban Innovation Vienna (UIV)

Finalised: December 2022

PROJECT INFORMATION
Project name: Decarb City Pipes 2050
Grant agreement number: 893509
Project duration: 2020-2023

DISCLAIMER

Table of Content

Table of Tables

Table of Figures

Executive summary

This report is the second out of three consecutive accounts of a coherent methodological framework developed in the EU Horizon 2020 project Decarb City Pipes 2050 to define heating and cooling decarbonisation design approaches for cities based on urban typologies. The first and third accounts are, respectively, the deliverable reports D2.5 (Decarbonisation design approaches based on urban typologies) and D2.7 (Recommendations for cities' H/C supplies & demands in 2050). The framework has been developed by identifying possible thematic synergies between the objectives of the concerned deliverables, by combining different method elements, and by organising a collaborative work strategy among the involved project partners. This report presents, in overview and detail, the input data synonymously used within the framework for the determination of urban typologies, for the modelling and mapping of heating and cooling outlooks for 2050, for the quantification of a cross-city synthesis, as well as for formulating recommendations for cities´ heating and cooling demands and supplies in 2050. The study focusses on the urban areas of seven European project cities (Bilbao (ES), Bratislava (SK), Dublin (IE), Munich (DE), Rotterdam (NL), Vienna (AT), Winterthur (CH)), for which EU-scoped, publicly available input data, to the extent possible, has been gathered according to ten structuring criteria parameters. Heating and cooling outlooks for 2050 are established for each project city based on the used input data and illustrated in the form of tables, graphs, and maps, and constitute the first element of a quantitative cross-city synthesis (city comparison). The second element (city ranking) is facilitated by application of a multi-criteria decision model, which here consists of combining the Analytical Hierarchy Process method (AHP) and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS).

1. Introduction

Over the last decade, the European community has become increasingly aware of the significant share that heating and cooling (H/C) energy demands constitute in the total final energy consumption of the European Union (EU). In fact, heating and cooling services such as space heating (SH), domestic hot water preparation (DHW), and process heat (PH), account for approximately half of this final energy consumption [1]. Despite a steady average increase of the share of renewable energy sources used in the EU27 H/C supply mix during the last twenty years (from 11.7% in 2004 to 22.1% in 2019 [2]), the sector is still carbon-intensive due mainly to continuous dependencies on fossil fuels such as natural gas, fuel oil, and coal.

These dependencies are problematic not only from local air quality and atmospheric carbon dioxide emission perspectives, but also in view of resource efficiency (since the use of high energy-quality fuels for low-temperature energy demands is synonymous to exergy destruction), energy efficiency (since only a minor part of these fuels are used for cogeneration of heat and electricity), and energy security (since considerable parts of these fuels are imported from outside the EU). For these reasons foremost, the decarbonisation of the heating and cooling sector in Europe represents an opportunity and a decisive measure by which to reduce overall primary energy demands and greenhouse gas emissions associated to the EU energy balance.

This context is the main outset for the EU Horizon 2020 project Decarb City Pipes 2050 (hereafter abbreviated "DCP2050 project" or just the "project")[1]. The DCP2050 project objective is to accelerate the process of urban transition to energy efficient and zero-carbon H/C solutions by strengthening planning and implementation capacities within cities. It is the first project to unite cities across Europe to work out actionable and spatially differentiated *Transition Roadmaps* to decarbonise their heating and cooling sector in 2050. The six cities of Bilbao (Spain), Dublin (Ireland), Munich (Germany), Rotterdam (the Netherlands), Vienna (Austria), and Winterthur (Switzerland), have organised Local Working Groups (LWG) that are committed to address this challenge. A seventh city, Bratislava (Slovakia), is part of the project as participant in capacity building activities and by contributing experience to peer-to-peer exchanges.

1.1. Objective and structure

This report is the sixth (out of seven[2]) deliverable outputs from Work Package 2 (WP2[3]) of the project, and the third account (out of three) with explicit focus on the H/C outlooks that are elaborated as steeping stones towards the final transition roadmaps for 2050 in each participating city.

[1] Project No. 893509, full title: Decarb City Pipes 2050 - Transition roadmaps to energy efficient, zero-carbon urban heating and cooling.

[2] D2.1: Input for H/C outlook 2050 (report (ppt), confidential); D2.2: Draft recommendations for H/C outlook 2050 (report, confidential); D2.3: Techno-economical possibilities and system correlations (report (ppt), public); D2.4: Report on data needs, accessibility etc. (report, public); D2.5: Decarbonisation design approaches based on urban typologies (report, public); D2.6: H/C outlook 2050 of cities with cross-city synthesis (this report, public); and D2.7: Recommendations for cities' H/C supplies & demands in 2050 (report, public).

[3] WP2 title: Heating and Cooling Outlook 2050. Lead beneficiary: Halmstad University (SE).

The first account was the initial kick-off presentation *Input for H/C outlook 2050* (Deliverable 2.1) on expected H/C supplies and demands in 2050 for EU, which was prepared in project month 3 (September 2020). The second account, the *Draft recommendations for H/C outlook 2050* report (Deliverable 2.2), was prepared in project month 12 (June 2021) and served the main purpose of providing first order responses (draft recommendations) to a set of *H/C supply outlooks 2050* that each LWG reached agreement upon under Milestone 2 (MS2[4]) in project month 11 (May 2021). These two first accounts were both associated with dissemination level confidential and were thus available only for members of the consortium (including the Commission Services). As will be further described below, an additional account referring to H/C outlooks will be conceived and communicated in the final deliverable output from WP2, the more generally formulated *Recommendations for cities' H/C supplies & demands in 2050* (Deliverable 2.7), originally scheduled for project month 27 (September 2022).

During the course of the project, the lead partners of WP2 (Halmstad University in Sweden and the City of Vienna in Austria) have discussed and considered different methods, approaches, datasets, as well as conceivable results, for the associated deliverable outputs. As preparations for the completion of the three final WP2 deliverables started (during the spring of 2022), that is for deliverable 2.5 (Decarbonisation design approaches based on urban typologies [3]), deliverable 2.6 (H/C outlook 2050 of cities with cross-city synthesis (this report)), and deliverable 2.7 (Recommendations for cities' H/C supplies & demands in 2050 [4]), the authors envisioned, outlined, and realised, that one single comprehensive approach could be developed and used to simultaneously meet the objectives of all three deliverables within one coherent methodological framework. This was made possible by identifying possible thematic synergies between the work descriptions of the associated WP2 tasks and by organising a collaborative strategy for its execution, as well as by combining different method elements and distributing the full framework account over three separate deliverable reports (as further described in section 2 below).

Hereby, this report represents, and should be understood as, the second (out of three) separate accounts of this coherent methodological framework developed to, firstly, define decarbonisation design approaches based on urban typologies, secondly to present quantified H/C outlooks for 2050 and a cross-city synthesis for the DCP2050 project cities, and, thirdly, to formulate and communicate general recommendations for urban H/C supplies and demands in 2050.

For clarity and overview, this conceived master structure is reproduced in the following bullet point list:

- *D2.5: Decarbonisation design approaches based on urban typologies*
    - Deliverable 2.5, report, public (scheduled for project month 26, August 2022)
    - Account focus:
        - Definition of urban typologies by use of a classification applied to data gathered for ten structuring criteria and participating cities

[4] Milestone 2 title: H/C supply outlook 2050. Means of verification: Common understanding among LWG with working hypothesis on how to reach carbon-free H/C energy balance. A draft outlook of H/C supply 2050 broken down to energy carriers is available for all cities (except Bratislava).

        - Detail of the applied Analytical Hierarchy Process (AHP) method, including structuring criteria questionnaire and found criteria weights
        - Formulation and outline of decarbonisation design approaches based on urban typologies

- *D2.6: H/C outlook 2050 of cities with cross-city synthesis*
    - Deliverable 2.6, report, public (scheduled for project month 26, August 2022)
    - Account focus (this report):
        - Detail and overview of underlying data assembled for ten structuring criteria presented as H/C outlooks for 2050 and participating cities
        - Overview recapitulation of the applied Analytical Hierarchy Process (AHP) method, including full account of data sources and references for ten structuring criteria
        - Detail of city comparison and city ranking (by application of TOPSIS method) in a cross-city synthesis
- *D2.7: Recommendations for cities' H/C supplies & demands in 2050*
    - Deliverable 2.7, report, public (scheduled for project month M27, Sept. 2022)
    - Account focus:
        - General recommendation for cities expressed as conclusions and findings emanating from D2.5, D2.6, as well as other project reports.

The main objective of this report, consequently, is to present H/C outlooks for 2050 for the participating cities in accordance with ten structuring criteria (see further section 2.2.1), used simultaneously within the framework both to define urban typologies and to quantify these outlooks. In addition, the objective is also to provide a cross-city synthesis of the participating cities, facilitated by quantitative comparisons partly with respect to total magnitudes and relative shares of the elaborated data parameters, partly with respect to a ranking procedure based on a multi-criteria decision analysis.

Hereby, this report aims to probe into possible future energy landscapes of the participating cities, to provide data-based indications of these, to produce material for discussions of likely developments depending on unique local conditions, and, finally, to present a plausible solution to the challenge on how to perform a quantitative cross-city synthesis.

As a general introduction to the topics and the ten selected structuring criteria elaborated in this report, subsection 1.2 presents and discusses in brief some *Key Concepts* by which the wider context encompassing these topics may be perceived (indicated by ***bold italic*** font). These key concepts have been chosen freely by the authors, however, not completely at random since they are thought to resemble closely related dimensions and ideas associated to the ten selected structuring criteria. All presented key concepts are also listed among the concluding remarks in section 6.

1.2. Key concepts in brief

While the European community has emerged as a global forerunner in terms of environmental and ecological insight during the last decade, among other indicated by an impressive production of legislative acts and reforms within the fields of ***Energy Efficiency***, ***Renewable Energy*** [5], and future ***Green and Circular Economies*** [6-8], the decarbonisation of H/C systems represents an area still in need of substantial reform and transition. In this respect, an overarching key concept which encircles the entire topic at hand is that of ***Directed Change***, that is, the deliberate action to steer events in a certain direction with control of its consequences. Although there is little controversy remaining in the EU today regarding the empirical evidence that lie beneath the visions and goals towards which these activities are aiming (support for energy system transformation and societal change), the ambiguous nature of directed change itself imposes principal difficulties upon any initiative that seeks to guide human actions towards a given goal. To control societal developments towards certain objectives and targets will always be associated with uncontrollable elements and consequences, why we seldom should expect the changes that we have actualised to result in exactly the outcomes we had in our aim. Ideally, by such a recognition, we could learn to maintain greater tolerances and margins when designing future transition programs, and to put emphasis on a few general objectives rather than on a thousand detailed paragraphs[5].

How then should one approach the call for change, the necessity to improve on our old ways, to transition, to transform, not just by accident, but by deliberate action towards a pre-conceived and well-defined target? Well, one first directly related key concept to consider would be that of ***Path Dependency***, that is the “business as usual” and the “standard procedures” of our ways, by which we, through unpremeditated continuation, together formed the existing system. Path dependency is symptomatic of our inability to do things differently than we did before, and – in facing the severe challenges at hand (associated to climate change, decarbonisation of energy provisions etc.) – simply must be addressed in any solution anticipating change and transformation. A useful way of contemplating this key concept may be to recognise its close kinship with routine and habit: What, who, and when need to change routine and habit? The “why” may be left out of the question since it is an already answered item.

Another key concept highly relevant is that which has become known as ***Technology Lock-in***, which relates to the fact that investments in energy infrastructures most often have long time horizons and that, therefore, there is a risk for lock-in effects in distributed systems dominated by one single technology solution. Another way of expressing this effect is to say, in the realm of heating and cooling services to buildings, that what is distributed for final consumption is a fuel and not a commodity. In the case of individual natural gas, for example, distributed directly to buildings, the provision represents a technology lock-in since the actual service (heat for SH and DHW) is excluded from the delivery itself and, in fact, only available after local conversion (combustion in situ). In comparison, a district heating system, which very well may be using the same fuel, that is natural gas (however, by way of central supply), avoids the technology lock-in effect since it distributes not a fuel, but the sought service itself. In this respect, the district heating system avoids not only the technology lock-in effect but maintains, as well, a higher degree of flexibility at the supply side.

Appearing thus almost as an opposite to technology lock-in effects, ***Flexibility*** may consequently by itself be considered a key concept under the topic at hand. While being a typical characteristic of central supply solutions, flexibility is closely related also to the

[5] Hobbes, T. , 17th century English philosopher, author of the famous “Leviathan” (The Matter, Forme and Power of a Commonwealth Ecclesiasticall and Civil, 1651), put forward already 370 years ago, as one of the most important characteristics of legislation in general (the rule of the sovereign), that it must be understandable to “the ordinary man”, that is, simple and clear rather than complicated and dodgy.

overarching key concept of ***Energy System Integration***, which points towards the systemic benefits obtainable with higher degree of interconnectivity between main energy system sectors, such as power, gas, and thermal networks. In the heating sector in particular, district heating systems equipped with cogeneration units, power-to-heat capacities, and thermal storages, are capable of providing systemic benefits to the power sector in the form of balancing capabilities (both production and consumption of electricity). The emergence of so-called ***Prosumers***, buildings with distributed generation of, for example, solar-based electricity and geothermal-based heat, thus simultaneously both “producing” and “consuming” energy services, are examples of energy system integration at the individual building level.

Another area of useful key concepts to consider is that of ***Demography***, where in particular projected ***Population Development Trends***, in this case especially for the year 2050, are important and also included among the studied structuring criteria. In this context, not only total population numbers may be of interest but also the expected share of city dwellers in the years to come, i.e. the ***Urbanisation Rate***. Directly related to such population numbers are of course also ***Building Energy Demands***, which, with respect to heat demands, for several reasons (increasing building renovation rates, improved building standards, reduced specific heat demands (heat demand by square meter floor area) etc.), are expected to continue decreasing in the coming years towards 2050 (not so for cold demands, which on the contrary are expected to increase). In addition, if taking the spatial concentration of specific building energy demands into account, that is their sum over a larger land area such as a hectare or square kilometre surface, the pivotal key concept of ***Heat Demand Density*** may be formulated and quantified (similar for cold demand density).

There are several reasons why the key concept of heat demand density is of special relevance in this context. Most prominently, as elaborated for example in [9], it may be used as a parameter by which to determine physical and economic suitability for different heat supply technologies. Moreover, if associated to a classification scheme by discrete intervals (as for example by Danish standard [10]), it may be used to determine general viability of different energy efficiency measures considering spatial circumstances at ***Local Conditions***. Under the topic at hand, local conditions may deservedly be treated as a stand-alone key concept in its own right since it is one of the fundamental pillars upon which contemporary energy system modelling and mapping rests[6] (see for example refs [11-13] This necessity to include and evaluate the local dimension in accordance with current day research approaches within the field of energy system analysis is, in this sense, itself a main driver for the anticipated structure and appropriate design of this project: the transition process originates in, is organised and managed by, and addresses exclusively, the unique local conditions in each of the participating cities.

Among additional key concepts to be discussed here in brief, could be mentioned also the two principal dimensions of ***Energy Efficiency Measures*** elaborated in this work, that is ***Structural Energy Efficiency Measures***[7] and ***Individual Energy Efficiency Measures***[8]

---

[6] The recognition at the heart of the novel methodological approach put forward by the Heat Roadmap Europe consortia in 2012, which, in short, was to combine high-resolution spatial mapping with energy system modelling to better understand opportunities for increased energy efficiency and use of renewable energy resources in the building sector, was the fact that thermal infrastructures – unlike both power and gas infrastructures – are strictly local.

[7] Technical/systemic measure reducing primary energy demands by increased recovery efficiencies in central or local conversion while maintaining equivalent end use levels.

[8] Technical/systemic measure reducing primary energy demands by absolute decreases of end use energy demands and/or by increased conversion efficiencies in central or local conversion while reducing equivalent end use levels.

[14]. Any reduction of the primary energy demand in an energy system must be conceived as an energy efficiency measure. However, whereas this efficiency gain can be obtained by central solutions, for example by supply side investments in district heating systems and excess heat recovery technologies (increased recovery efficiencies), it may likewise be obtained by individual solutions, for example demand side investments in heat saving measures in buildings (end-use demand reductions) and more efficient end-use applications (increased conversion efficiencies). Since these different measures are associated with different costs (at different conditions), they are useful for the determination of a cost-optimum between them, which in turn can inform of the most feasible cost solutions at the system level.

An alternative nomenclature for the former of these energy efficiency dimensions may be that of ***Supply Side Energy Efficiency Measures***, which thus reduces primary energy demands of the system by improving the system structure, i.e. by reducing the amount of unused heat losses from energy conversions through waste heat recoveries (for further references, see for example [15]). Complementary, for the latter of the two, ***Demand Side Energy Efficiency Measures***, reduce the primary energy demand of the system by reducing the absolute magnitudes of final end-use demands in the system, that is by direct heat savings through, for example, improved insulation of building envelopes, by replacement of windows and other building components, by use of ***Best Available Technologies (BAT)*** in end-use conversions (hereby exploiting higher conversion efficiencies in final consumption) and so on.

One important difference between these two types of energy efficiency measures, despite their different cost levels and varying investment lifetime horizons, is the fact that the former (structural energy efficiency measures, or supply side measures) implies no reduction of final end-use levels since the efficiency gains here originate in an improved system structure. In the latter case (individual energy efficiency measures, or demand side measures), the opposite is the case; the system itself remains relatively inefficient but still manages to reduce its primary demands since final end-use demands have been lowered.

A contextual consequence of this dynamic is therefore that – depending on the local conditions at hand – over-prioritisation of the one may in effect make impossible the other, since, for example, a district heating system needs a certain level of useful heat demand to serve in order to be economically feasible. This dynamic is therefore also a main underlying driver for striving to always identify the optimal balance between supply and demand side investments, respectively, thus, to identify and organise the most appropriate system at lowest cost by avoiding ***Sub-Optimisation*** and technology lock-in effects.

A final key concept to mention before ending this subsection is that of ***Temperature Levels***, both with respect to energy assets (heat supply sources), energy demands (building heat demands), and energy infrastructures (heat distribution networks). By themselves, temperature levels associated with heating and cooling services to buildings are becoming increasingly important, in particular when considering future applications and conditions, where the common denominator is their mutual expected decrease in coming years. This development is closely related to the historical development of district heating itself (stretching back to the late 1870s and the state of New York in the United States of America [16]), but in particular so to its most recent progress towards so-called low-temperature systems, often referred to as the 4th and the 5th generations of district heating technology. As further detailed for example in refs. [17-22], such low-temperature systems are assumed to represent best-available thermal network distribution technologies in the period from 2020 to 2050, and are associated with maximum supply and return temperatures in the order of 70˚C/30˚C.

The reduced operational temperature levels of future district heating systems, compared to current 3rd generation district heating systems, with corresponding operational temperature levels in the approximate order of 100˚C/45˚C, are of utmost importance for the facilitation of higher integration levels of renewable energy sources, such as solar thermal and deep geothermal, into these systems. The same may also be said with respect to the recovery of current, and in particular, future waste heat resources, a field of opportunity which by reduced operational network temperatures expands from the direct reuse from conventional sources (such as power plants, Waste-to-Energy plants, and energy intensive industrial activities), into a wide range of additional unconventional sources (such as data centres, waste water treatment plants, refrigeration processes in food production and retail etc.), sources which are included among the elaborated waste heat resources in this analysis.

Furthermore, since reduced operational temperatures also reduces the average temperature difference to the surrounding ambient, this in turn reduces the amount of distribution heat losses associated with low-temperature heat distribution, which thus represents a plausible efficiency gain in such future systems. For the above reasons, the successful deployment of new low-temperature heat distribution systems, as well as the transformation of many existing district heating systems to lower operational temperatures, represent important concrete steps that can contribute to a successful transition of European heating and cooling services for buildings.

1.3. Scope and limitations

Data and results presented here, being integral parts of the above-mentioned coherent methodological framework, are limited to the seven project cities and their near surroundings (the analytical field stretches at most 100 kilometres from the geographical centre points of these cities). However, given the deliberate use within this framework of publicly available datasets with a continental-wide European scope, for comparability and replicability purposes (see further section 2.1), any city in Europe for which such data may be found could apply the framework and produce results of their own.

The use of continental-wide datasets, which often are the result of generic, top-down, modelling and mapping approaches, regrettably comes at the cost of somewhat lesser detail with regard to the specific circumstances of local phenomena. It is, for example, seldom possible to assess, with perfect precision, the exact magnitude of available waste heat on an annual basis from a waste water treatment plant operating in the outskirts of any given city in Europe – especially not when this plant is one among ~23,000 in a comprehensive datasets covering a multitude of countries with different climate zones, different jurisdictions, different operational strategies etc. (for more information on the used dataset on low-temperature waste heat sources, see further section 2). Despite this limitation, first-order assessments, as often given by generic data, are still of great value for orientation and direction during initial phases of strategic heat planning [23]. In later (or parallel) stages, however, genuinely local, specific, bottom-up, approaches, should follow with access to unique local level data (municipal, city administration, operator, utility etc.) in the preparation of dedicated transition roadmaps [24-26].

Regarding the ten structuring criteria elaborated in the coherent methodological framework, as briefly mentioned above, it may be appropriate to comment here that these have been chosen, carefully selected, one might say, considering both relevance to the topic at hand and the availability of data to allow quantification. But, given other contextual circumstances, other criteria could certainly be relevant. In this respect, the first of our three framework accounts [3], provides several useful examples of other plausible structuring criteria and urban typology definitions that can be used to determine decarbonisation design approaches for cities. Notably, although applicable at any level of spatial resolution, such as neighbourhoods, city districts, towns, as well as entire metropolitan areas, the classification of urban typologies used here has been performed at a level of resolution corresponding to coherent, inner-city urban areas[9] (as detailed further in section 2.1 below), where the recently developed, publicly available, "Urban Areas" dataset from the EU Horizon-2020 project sEEnergies, have been used for the spatial characterisation of participating cities [27, 28].

Another limitation in the used framework approach, is that underlying data for the Swiss partner-city of Winterthur was quite often simply not available among the used datasets (predominantly targeting EU27 member states plus the United Kingdom only). There are exceptions, for example regarding data used to assess biomass potentials, but, in general, mainly due to lack of generic-level data, Winterthur is only partially represented in the following analyses and results. On the other hand, the LWG in Winterthur has extensive knowledge of local data and site-specific circumstances, and have further agreed both on an H/C outlook for 2050 and a H/C map on this basis. Finally, discussions and final conclusions regarding our results are touched upon only briefly here, since they constitute the core elements of the third and final framework account [4].

[9] For the city of Rotterdam, only the urban areas north of the Nieuwe Maas channel (a part of the Rhine–Meuse–Scheldt delta which leads out to the North Sea) is included in this analysis due to an initial misinterpretation of the areas south of the channel as mainly consisting of industrial areas (see further subsection 3.2.5). Also, four additional cities are included in the urban areas north of the channel (Schiedam, Vlaardingen, Capelle aan den IJssel, and Krimpen aan den IJssel). This is an unfortunate limitation in the framework application and the results for the city of Rotterdam should be viewed with this shortcoming in mind.

2. Data and methods

This report consists at its core of two main contents. On the one hand, H/C outlooks for 2050, which principally refer to data-based characterisations and analyses of expected supplies, demands, and infrastructures available in the seven project cities some thirty years into the future. On the other hand, multi-criteria decision modelling, which incorporates applications of the Analytical Hierarchy Process method (AHP) and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) ranking method to facilitate a cross-city synthesis (for further information and references, see subsections 2.2.2 and 2.2.3, respectively).

Common for both of these core constituents are a set of structuring criteria (ten parameters, see further subsection 2.2.1) by which urban areas, city districts, towns, and whole cities, may be characterised regarding the objective to decarbonise heating and cooling services. These ten structuring criteria have been carefully selected considering both relevance to the topic at hand and the availability of data to allow quantification, and they all relate, directly or indirectly, to the supply, distribution, and end use, of energy for heating and cooling services.

The main data sources used for this data-based characterisation are, to the extent possible, publicly available datasets that anyone can download from online repositories, statistics providers, web map interfaces, and other open information resources. In most cases, the used data have been accessed with the sought data parameters already included among the downloaded contents, in some cases, the accessed data has had to be subjected further calculations and analyses in order to establish the sought input parameters (the ten structuring criteria). Noteworthy, the ambition was to gather underlying data which reflect conditions for the future year of 2050, where available, in order to establish a basis for H/C outlooks, cross-city synthesis, and recommendations for this default future year setting.

In terms of tools and software, the Geographical information systems (GIS) architecture provided by ESRI's ArcGIS Pro (version 2.9.3) application has been used for management, production, analyses, and visualisation, of spatially related data. The assembly of ten structuring criteria, including the corresponding underlying input data parameters, the corresponding classification to define urban typologies, and the associated decarbonisation design approaches, have mainly been managed within Excel. For the final multi-criteria decision modelling, a special software, the Super Decisions software [29], was used.

2.1. Publicly available data

After a decade of ground-breaking continental-level EU-projects, which have investigated local conditions basically from top-down perspectives, such as the above-mentioned Heat Roadmap Europe project, 2012 to 2019 (in a series of related projects) [11], the Hotmaps project, 2016 to 2020 [30], the ReUseHeat project, 2017 to 2022 [31], the sEEnergies project, 2019 to 2022 [32], plus several others, a rapidly increasing number of (generic) data pertaining to energy services in the EU building sector has started to become publicly available through open data sharing policies. Despite the fact that data derived by such top-down approaches likely suffers from a certain lack of local precision, briefly touched upon in subsection 1.3 above, two principal benefits of its use is the facilitation of comparability, on the one hand, and replicability, on the other.

2.1.1. For comparability

The use of publicly available data sources in the coherent methodological framework, as detailed in Table 1, is motivated first by the fact that the seven participating project cities may be characterised by the same datasets. This is advantageous in view of performing a cross-city synthesis based on quantitative metrics, since it enables a fairer comparison.

TABLE 1. OVERVIEW TABLE OF MAIN DATA SOURCES USED IN THE COHERENT METHODOLOGICAL FRAMEWORK (SPECIFIC REFERENCES TO PARTICULAR DATASETS ARE GIVEN IN THE TEXT AS THEY APPEAR)

Main data sources	Provider	Main reference
Pan-European Thermal Atlas 5.2	sEEnergies	[33]
The European Waste Heat Map	ReUseHeat	[34]
Enspreso Biomass	Joint Research Centre	[35]
Mapping and planning tool for heating and cooling	Hotmaps	[30]
Pan-European Thermal Atlas 4.3	Heat Roadmap Europe	[36]

2.1.2. For replicability

The second main motive for using publicly available data sources is the sheer fact of it being publicly available. The availability of the used data, it being accessible and downloadable from reachable portals, enables direct replicability of the conceived approach. As such, this could bring valuable opportunities for other cities in the EU who are interested in decarbonising their heating and cooling sectors and develop transition roadmaps for the future. In this respect, noteworthy, as also further indicated in Table 3 below, not all of the data sources used to quantify the ten structuring criteria have been found among known public repositories. However, seven datasets out of ten are indeed publicly available.

2.2. Multi-criteria decision model

A core element of the coherent methodological framework is multi-criteria decision modelling, which is used to distinguish the relative importance of each identified and selected structuring criteria parameter relative to the overarching objective to decarbonise H/C services within cities. The multi-criteria modelling itself rests on the basis of an AHP, as further explained in subsection 2.2.2 below, which is applied in two different ways within the coherent framework depending on the study purpose.

In the D2.5 deliverable report and context [3], on the one hand, the five (out of ten) structuring criteria with the highest relative importance (expressed as weights, according to expert opinion, and as depicted in Figure 3 below) are used to define and characterise three distinct urban typologies to which, in extension, corresponding decarbonisation design approaches are associated (two design approaches per typology; one long term and one short term). In the context of this report, on the other hand, the expert evaluation of all ten structuring criteria is considered in a TOPSIS-based analysis to facilitate a quantitative cross-city synthesis. In the former, the AHP is thus used to determine which decarbonisation design approaches are most suitable for any given urban typology, while here, in the latter, the AHP weights are used as to sort and rank the alternatives based on their distance to an ideal and an anti-ideal solution.

2.2.1. Structuring criteria

The ten structuring criteria parameters, or indicators, which have been selected within the coherent methodological framework are outlined in Table 2 with descriptions. The selection process has considered relevance, comparability, and data availability of the structuring criteria, and moreover divided these into three main categories (Energy supply, Energy demand, and Energy efficiency), as presented in Table 3 and Figure 1 below. Table 3 further details how the structuring criteria have been defined within the framework, the units of the used input data parameters, their main source references, as well as indications for their public availability at the continental-wide EU-scale.

Table 2. The ten structuring criteria considered in the coherent methodological framework for the decarbonisation of urban heating and cooling systems

No.	Criterion	Description
1	Coverage of district heating	Current and future deployment level of district heating
2	Potential for renewable sources	Local/regional potential for renewable energy sources, such as sustainable biomass, geothermal, solar energy, etc.
3	Potential for waste heat	Local/regional potential for waste heat, considering all possible sources such as power plants, iron works, paper and pulp plants, data centres, wastewater treatment plants, etc.
4	Dependency on fossil fuels	Current and future dependency on natural gas, oil, coal, and other fossil sources for heating and cooling purposes in buildings
5	City population	Projected city population in 2050
6	Heating index	An adjusted version of the ordinary Heating Degree Day concept, which, among other, takes into consideration the typical level of building insulation used in different European countries
7	Heat Demand Density	The spatial concentration of building heat demands for space heating and domestic hot water preparation, often expressed as MWh per hectare or similar
8	Development of the built environment	The expected development of the built environment with respect to residential and service sectors expressed as the modelled evolution of floor areas
9	Individual energy efficiency	Energy efficiency measures with end-use application address, typically energy savings in buildings by, for example, refurbishments, window replacements, increased insulation, etc.
10	Structural energy efficiency	Energy efficiency measures applied on the supply side of the energy system which obtains reduced primary energy demands by more efficient conversion and distribution (for example, district heating systems)

It should be noted that also other datasets, other than those listed in Table 3, have been used in the performed analyses. This includes, for example, standard datasets for European administrative units, such as countries and NUTS2 regions, accessible at Eurostat [37], and, among other, the Corine Land Use dataset out of Copernicus [38], as well as a useful sEEnergies project dataset which outlines locations and anticipated spatial outreach of current district heating areas in the European Union [39-41].

Table 3. Input data characteristics for the ten structuring criteria by main category, definition, unit of input data, and source references

Main category	No.	Definition	Unit	Source	Publicly available at EU-scale
Energy supply	1	Current relative shares in the city as stated in internal project report	[%]	[42]	No
	2	Enspreso Reference scenario potential for biomass in 2050, apportioned to urban areas by 50 km and 100 km radius from city centres	[PJ/a]	[43]	Yes
	3	Current potentials for conventional and unconventional sources, inside, within 10 km, and within 25 km of urban area perimeters	[PJ/a]	[34]	Yes
	4	Sum of "Gas" and "Oil" in the city as stated in internal project report	[%]	[42]	No
Energy demand	5	Calculated as the relative difference between projected 2050 population and known 2015 population at hectare level	[%]	[44]	Yes

Main category	No.	Definition	Unit	Source	Publicly available at EU-scale
	6	The index is calculated based on 40 years' time-series data with sub-hourly measurements and established the local average for the given time period	[-]	[45]	Yes
	7	Calculated as the share of hectare cells out of the urban area total with heat demand densities above 120 TJ/km² under the sEEnergies Frozen Efficiency scenario (FE2050)	[%]	[46]	Yes
	8	Calculated as the relative difference between projected 2050 floor areas and known 2015 floor areas at hectare level	[%]	[47]	No
Energy efficiency	9	The sEEnergies Index sub-index "Building Efficiency" establishes a quota between projected 2050 building heat demands in a (more ambitious) Baseline scenario (BL2050) and a (more modest) Frozen Efficiency scenario (FE2050). This fraction is then subtracted from the number "one" (thus expressing the potential for individual energy efficiency as a percentage) and assigned a value between 1 and 10 by classification.	[n]	[48, 49]	Yes
	10	Calculated as the share of total urban area building heat demands, by hectare grid cells, that permits investments in district heating networks with marginal distribution capital costs at or below 10 €/GJ under the sEEnergies Baseline scenario (BL2050)	[%]	[50]	Yes

2.2.2. Analytical Hierarchy Process (AHP)

The Analytic Hierarchy Process (AHP) [51] is one of the most applicable and well-used multi-criteria decision-making approaches to make a decision based on experts' opinions. The general aim of the method is to select the best alternative among several choices considering a number of evaluation criteria. The AHP procedure ascertains the relative importance of criteria and alternatives as numerical weights. AHP data is generated following pairwise comparisons of criteria and alternatives by experts. In this way, the method converts a complex decision-making problem into a series of simple pairwise comparisons.

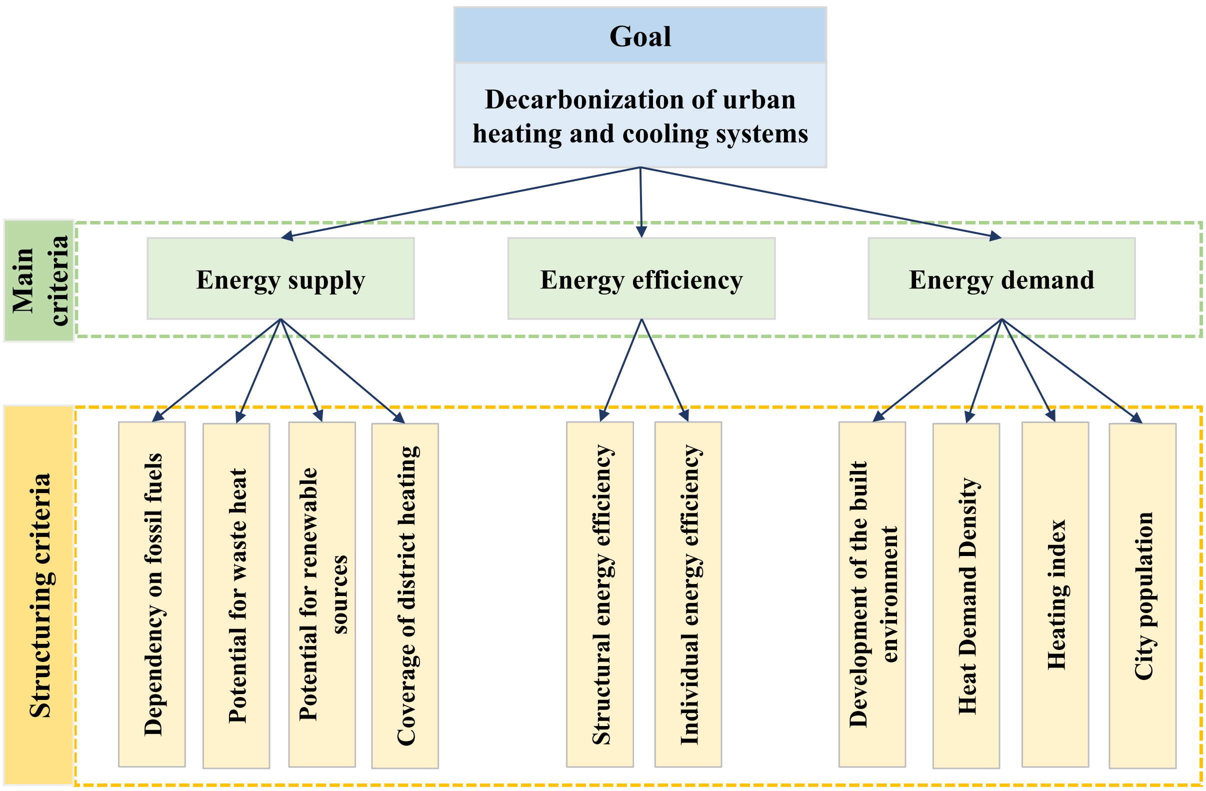


FIGURE 1. THE AHP HIERARCHY TREE FOR THE DECARBONISATION OF URBAN HEATING AND COOLING SYSTEMS.

The AHP method is composed of three steps [52]:

- ***Step 1. Structuring of the decision-making problem in a hierarchy tree***

The hierarchy tree of the decarbonisation problem is represented in Figure 1. It includes three levels of goal, main criteria (the main three categories of criteria), and structuring criteria. The goal is the decarbonisation of urban heating and cooling systems. The relevant elements of the hierarchy have been connected from top to bottom. These connections determine which elements are compared in pairwise comparisons.

- ***Step 2. Pairwise comparisons between the elements of the hierarchy***

The pairwise comparisons produced a questionnaire with 16 statements in which a numerical scale from one to nine was applied to express the relative importance, where a larger number indicates higher importance. Twenty-one energy experts, including professors, researchers, consultants, and project partners from three universities (Halmstad University (SE), Lund University (SE), and Aalborg University (DK)), four city administrations (City of Vienna (AT), City of Munich (DE), City of Rotterdam (NL), and City of Winterthur (CH)), and three other institutions and consultancies (Urban Innovations Vienna (AT), Technalia (ES), and Codema (Dublin Energy Agency) (IE)), were asked to participate in the survey and fill out the questionnaire. Among these, 12 completed questionnaires were collected (for the complete account of the questionnaire and the expert responses, see reference [3]). The participants' responses were aggregated to reach the group decision matrix, and the Super Decisions software was used to carry out the calculations.

- ***Step 3. Calculation of priorities (weights)***

The results as relative weights of the criteria categories and the structuring criteria are represented in Figure 2 (main categories) and Figure 3 (structuring criteria). Figure 2 illustrates that the energy supply, with 52% weight, is regarded as the most crucial criterion for decarbonizing urban heating and cooling systems, followed by energy efficiency (30%) and energy demand (18%).

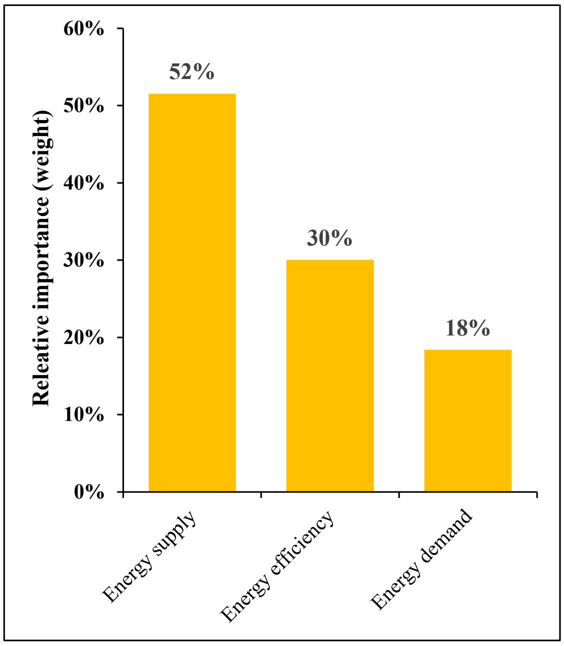


FIGURE 2. THE WEIGHTS OF THE THREE MAIN CRITERIA FOR THE DECARBONISATION OF URBAN HEATING AND COOLING SYSTEMS BASED ON THE EXPERTS' OPINIONS.

In Figure 3 it may be seen, as a result of the higher priority of energy supply and energy efficiency, that those structuring criteria which are associated with these two main categories have received further emphasis from the experts. Accordingly, based on experts' evaluations, "Structural energy efficiency" is the most important structuring criterion when deciding whether an urban area's H/C system is apt for decarbonisation. "Coverage of district heating" and "Potential for renewable sources" are the second and third important criteria, which both are related to the supply side.

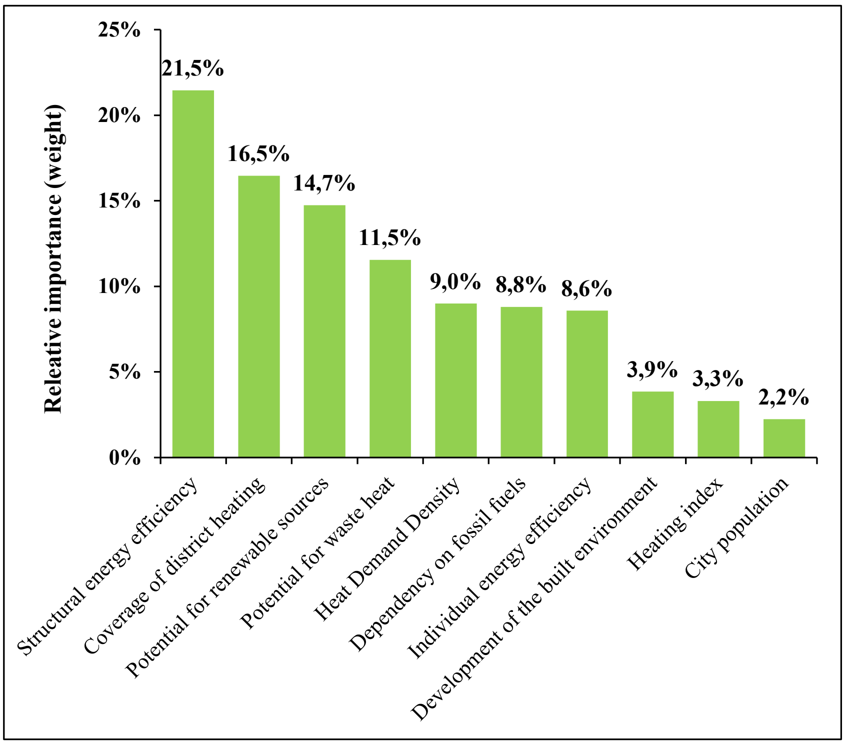


FIGURE 3. THE WEIGHTS OF THE STRUCTURING CRITERIA FOR THE DECARBONISATION OF URBAN HEATING AND COOLING SYSTEMS BASED ON THE EXPERTS' OPINIONS.

2.2.3. TOPSIS ranking

To perform a quantified cross-city synthesis regarding the appropriateness of different urban areas for heating and cooling decarbonisation by different measures and design approaches, it is necessary to compare the cities under study based on comparable data gathered for each of the considered criteria. This leads to a matrix of data on which analytical tools can be used to extract generalities. The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is a reliable multi-criteria decision analysis that has been implemented in many recent applications to deal with such decision matrices [53, 54].

TOPSIS is generally utilised to rank options, alternatives, solutions, or choices, respecting a number of measures, indicators, or criteria. The primary idea behind this approach is to find the best and worst alternatives and then calculate the distance of each alternative to two extreme solutions. The best alternative, then, is one that has the shortest distance to the best solution and the furthest distance to the worst solution. The note is that the best and worst solutions might not really exist. This is why they are called ideal and anti-ideal solutions.

The TOPSIS procedure to rank the concerned participating cities in terms of their suitability for different heating and cooling decarbonisation measures is carried out in six steps as follows [55]:

- ***Step 1. Determining the evaluation criteria***

The relative weights of ten structuring criteria resulting from the questionnaire responses are presented in Table 4 (the “AHP weight” column displays the found relative weight of each criterion). These weights have been obtained using the AHP method and based on the experts’ opinions, as described more fully in [3]. One of the TOPSIS method's benefits is its ability to take into account each criterion's relative importance when later ranking the alternatives.

Table 4. The considered criteria and their relative weight and direction for the decarbonisation of urban heating and cooling systems

Criterion	AHP weight	Direction
Coverage of district heating	16.5%	Forward
Potential for renewable sources	14.7%	Forward
Potential for waste heat	11.5%	Forward
Dependency on fossil fuels	8.8%	Reverse
City population	2.2%	Reverse
Heating index	3.3%	Reverse
Heat Demand Density	9.0%	Forward
Development of the built environment	3.9%	Reverse
Individual energy efficiency	8.6%	Forward
Structural energy efficiency	21.5%	Forward

As can be seen on the far right in Table 4, the “Direction” column, with two possible descriptions of “Forward” and “Reverse”, indicates how a criterion is interpreted in the decision-making problem. A “Forward” criterion means that alternatives with higher values under that criterion are more preferred and closer to the ideal solution. Vice versa, a “Reverse” criterion implies that alternatives with lower values in that criterion are more appealing to the decision maker.

Labelling a measure as forward or reverse is context-dependent and relies on the purpose of the decision problem. Depending on the study scope, the aim could be to determine which city, or city district, or urban area in general, that is most apt for decarbonising its heating and cooling system according to a given decarbonisation design approach. The focus here, in this report, is on the entire urban area of each respective participating city, not on the particular heating or cooling systems at building or neighbourhood level. Accordingly, the four indicators of “Dependency on fossil fuels,” “Development of the built environment,” “Heating index,” and “City population” are regarded as reverse criteria, and the remaining six are considered as forward indicators.

- ***Step 2. Providing the decision matrix***

To be able to sort the alternatives, it is inevitable to recognize the performance of each of the alternatives in each criterion. This yields an M*N data matrix, in which M and N are the number of criteria and alternatives, respectively. The decision matrix in our problem is a 10*6 matrix as there are ten criteria and six cities (alternatives). Winterthur has been removed from this analysis because of the lack of data. The resulting data matrix is presented in Table 19 in the results subsection 5.2.

- ***Step 3. Calculating the weighted normalized decision matrix***

Since the used criteria have different units, the scores must be normalized to become comparable. The TOPSIS method recommends using the sum of squares for normalization. Moreover, each matrix element ought to be multiplied by the weight of the relevant criterion to achieve the weighted matrix. The subsequent weighted normalized matrix thus is produced by using equation (1).

$$r_{ij} = w_j \frac{a_{ij}}{\sqrt{\sum_{i=1}^{M}\left(a_{ij}\right)^2}} \quad \forall\, i = 1,\dots,M \; and \; j = 1,\dots,N \tag{1}$$

where r_{ij} is the element of the weighted normalised matrix, w_j is the weight of criterion j, and a_{ij} is the element of the decision matrix. Table 21 in appendix subsection 8.2 shows the weighted normalized matrix of the decarbonisation problem at hand.

- ***Step 4. Determining the ideal and anti-ideal solutions***

The imaginary ideal solution is a vector whose elements consist of the maximum values of the forward criteria and the minimum values of the reverse criteria. Vice versa, the anti-ideal solution encompasses the minimum values of the forward criteria and the maximum values of the reverse criteria. Formulas (2) and (3) are used to attain the ideal and anti-ideal choices.

$$X_j^b = \max_{\forall\, i} r_{ij} \quad \forall\, j = 1,\dots,N \tag{2}$$

$$X_j^w = \min_{\forall\, i} r_{ij} \quad \forall\, j = 1,\dots,N \tag{3}$$

where X_j^b and X_j^w are elements of the ideal and anti-ideal solutions, respectively. Accordingly, the ideal and anti-ideal solutions are as shown in Table 22 in appendix subsection 8.2.

- ***Step 5. Computing the distances***

The TOPSIS initiative is to sort the alternatives based on their distance to the ideal and anti-ideal solutions. The Euclidean distance between each alternative and the two extreme solutions are computed via equations (4) and (5).

$$d_i^b = \sqrt{\sum_{j=1}^{N}(r_{ij} - X_j^b)^2} \quad \forall\, i = 1,\dots,M \tag{4}$$

$$d_i^w = \sqrt{\sum_{j=1}^{N} (r_{ij} - X_j^w)^2} \quad \forall\, i = 1, \dots, M \tag{5}$$

where d_i^b and d_i^w are the elements of the distance vectors from the ideal and anti-ideal solutions. The results are reported in Table 20 in the results subsection 5.2.

- ***Step 6. Ranking alternatives***

Alternatives that have a close distance to the ideal solutions and have a far distance to the anti-ideal solutions are ranked higher in the TOPSIS technique. For doing this, formula (6) is applied.

$$s_i = \frac{d_i^w}{d_i^w + d_i^b} \tag{6}$$

where s_i is the TOPSIS score for alternative i. The final ranking of the cities according to the ten structuring criteria constitutes part of the main study results and is therefore presented in the results subsection 5.2, see Figure 28.

3. H/C outlook 2050

As mentioned above, the H/C outlooks for 2050 presented in this section are solely based on the gathered input data for the ten considered structuring criteria elaborated in the multi-criteria decision model. The main rationale for this has also been stated above, e.g. direct comparability and replicability of the cross-city synthesis results, but it is worth emphasising here that this approach is exclusive only for the context of the coherent methodological framework developed for this part of the project work. For the LWG´s in the project cities themselves, no such limitation exists, neither now nor at earlier or later stages of the project duration.

On the contrary, as also reported in several other project outputs (see for example deliverable reports D2.4 (Report on data availability, data sovereignty, quality and exchange in the participating cities and policy recommendations [56]) and D3.3 (H/C plans of cities with cross-city synthesis [42]), a wide range of various data parameters and sources, other than those elaborated here, are available and used locally in each project city. In the following, where applicable and relevant, as this section begins by presenting a general city overview of the seven project cities and then continues with specific presentations of each of these cities under a conceived 2050 baseline scenario [49, 57], references may be made without further specification to such locally available data, locally developed H/C plans, as well as locally agreed H/C outlooks.

3.1. City overview

As a first orientation for the H/C outlook 2050 and the cross-city synthesis to be established in this report, this city overview begins with a closer look at anticipated future building heat demands in residential and service sectors, as outlined in Table 5. The table data refers to geographical datasets developed in the EU projects Heat Roadmap Europe (HRE4) and sEEnergies (see also Table 1), and consists of two current year estimates (BL2015 and BL2015 (HRE4)) and two 2050 scenario estimates according to, on the one hand, a Baseline (BL2050) and, on the other hand, a so-called Frozen Efficiency Scenario (FE2050)[10].

TABLE 5. END USE HEAT DEMANDS FOR RESIDENTIAL AND SERVICE SECTOR BUILDINGS BY URBAN AREAS (UA). DATA FROM HEAT ROADMAP EUROPE (BL2015 (HRE4)) AND SEENERGIES (BL2015) FOR 2015, AND BY SEENERGIES FOR A BASELINE (BL2050) AND A FROZEN EFFICIENCY (FE2050) SCENARIO. SOURCES: [9, 33, 49, 57, 58]

	[PJ/a]	[TWh/a]	[PJ/a]	[TWh/a]	[PJ/a]	[TWh/a]	[PJ/a]	[TWh/a]
Name	**FE2050**		**BL2050**		**BL2015**		**BL2015 (HRE4)**	
Bilbao	15.1	4.2	13.0	3.6	14.2	4.0	13.3	3.7
Bratislava	12.0	3.3	3.9	1.1	11.8	3.3	12.7	3.5
Dublin	18.8	5.2	10.2	2.8	18.7	5.2	19.1	5.3
Munich	36.8	10.2	25.9	7.2	39.4	10.9	39.8	11.1
Rotterdam	9.5	2.7	7.5	2.1	8.7	2.4	9.3	2.6
Vienna	47.8	13.3	36.9	10.3	49.1	13.6	53.2	14.8
Winterthur	-	-	-	-	-	-	-	-
Grand total	**140.1**	**38.9**	**97.5**	**27.1**	**141.9**	**39.4**	**147.5**	**41.0**

[10] Total EU27+UK end use heat demands for SH, DHW, and PH, in residential and service sectors (delivered/useful energy) were assessed at 3172 TWh/a in FE2050; at 2406 TWh/a in BL2050; at 3200 TWh/a in BL2015; and at 2978 TWh/a in BL2015 (HRE4).

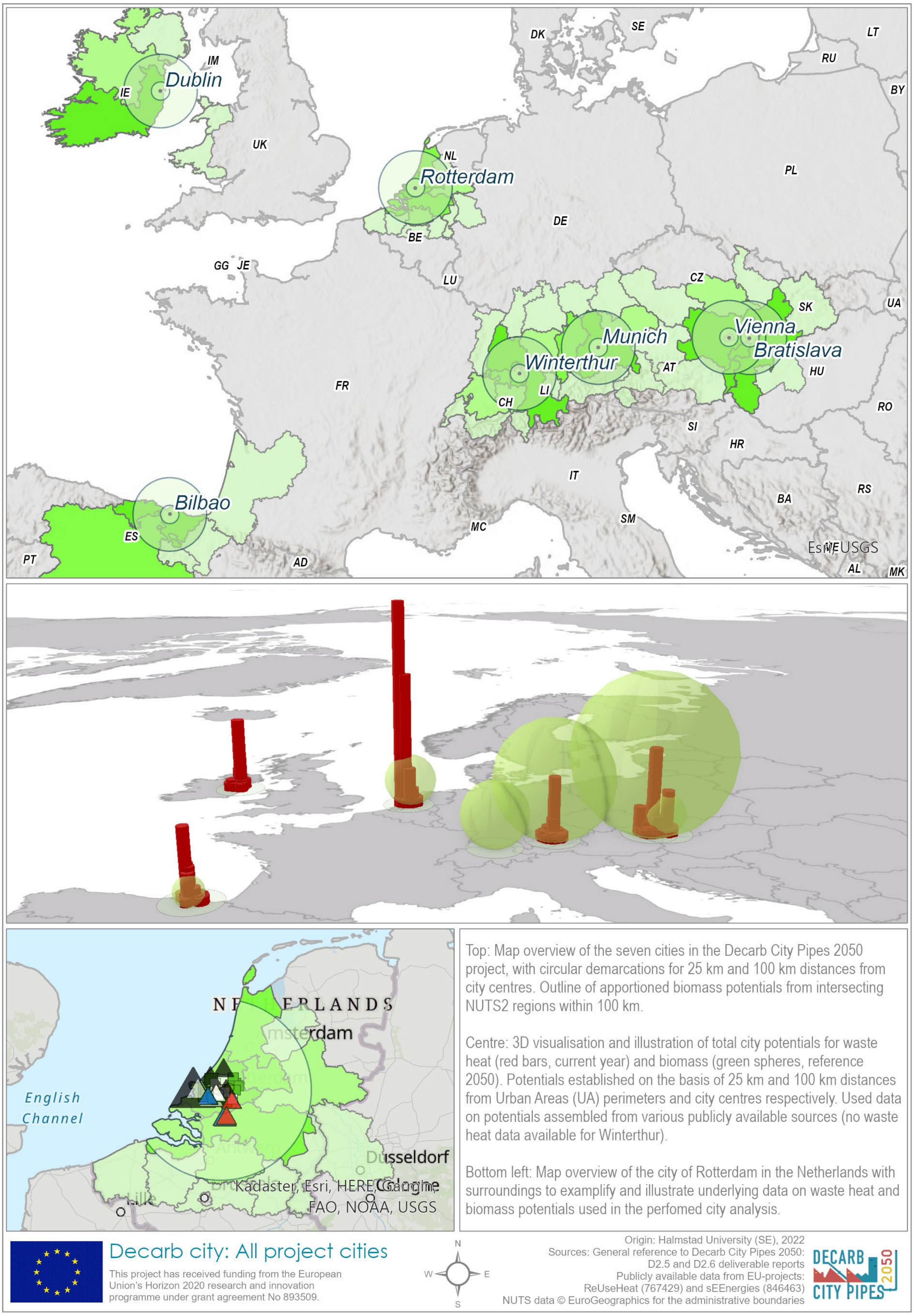


Figure 4. All cities map overview: The seven cities in the Decarb City Pipes 2050 project with outline and visualisation of total waste heat potentials within 25 km of Urban Areas (UA) perimeters, 2050 biomass potentials apportioned by 100 km distances to city centres, and spatial analytics example. Sources: [34, 43].

As can be seen in Table 5, there is no substantial discrepancy between the two current year estimates for 2015 regarding total city heat demands, which hover around some 40 TWh per year in total (excluding Winterthur). The projected 2050 heat demands on the other hand varies remarkably depending on which scenario that is considered. In the FE2050 scenario (which principally corresponds to a Business-as-Usual projection with no additional energy efficiency measures considered other than those adopted by current EU legislation), the total sum of cities' heat demands is similar to current levels while the BL2050 scenario represents an approximate 31% reduction relative to the base year (BL2015). By reference to the same difference, but under the wider scope of EU27 plus UK, the BL2050 scenario reduction (which in itself mainly consists of energy saving measures such as window replacements and refurbishments of building envelope elements, including façade painting), corresponds to minus 25% relative to the 2015 baseline, hence considerably less than the overall reduction in the project cities.

Noteworthy, the final energy system modelling outputs from the sEEnergies project (as detailed in ref. [58]), elaborates on two additional heat demand reduction scenarios for 2050 (the "Baseline +20%" and the "Baseline +30%"), where the total EU27 plus UK end use heat demand in the considered sectors, according to the BL2050 scenario, is further reduced and assessed at 1845 TWh per year and 1614 TWh per year respectively. Main drivers for these additional scenario reductions are anticipated application of more ambitious building standards in the EU, as well as renovation rates above otherwise modelled annual average levels of 1% per year. Being among the final modelling outputs from the sEEnergies project, regretfully, none of these additional scenarios were projected geographically, which is why they are not available among the published spatial datasets used in this context.

Now, for further orientation, Figure 4 presents an all-cities map overview in order to draw attention to some key characteristics of the seven under-study cities, as for example their geographical locations and their general access to waste heat and renewable energy sources (here represented by residual-based biomass), as well as to exemplify how underlying data may be used in spatial analytics.

From the top map in Figure 4, it can be seen that the project cities fairly well represent some distinctly different European geographic regions: Bratislava, Munich, Vienna, and Winterthur from central Europe, Dublin from the northwest, Bilbao from the southwest, and Rotterdam from the central/west. The variety in geographic regions can be a source of assorted climate types. This diversification ranges from oceanic, cool, and humid weather in Dublin to dry continental climate in Vienna, sub-oceanic and rainy climate in Rotterdam, and warm and temperate weather in Winterthur. This, in turn, would be a root cause for the presence of different patterns of energy demand in general and of heating and cooling demand in particular. Accordingly, different heating and cooling decarbonization strategies and approaches may be needed for each city due only to this factor alone.

However, the energy demand aspect is only one side of the main criteria triangle we are considering for this analysis, as indicated above in Figure 1 and Figure 2. To what extent and in which forms energy resources are available is another key issue, which itself also may be subject to geographic conditions. To exemplify this second side of the triangle, the energy supply aspect, the middle map in Figure 4 displays the cities' total renewable and waste heat potential, as found among the selected structuring criteria. As seen by red bars and green spheres, Rotterdam has clearly the highest waste heat potential, and Vienna is a city that possesses the largest biomass resources.

It is in place to note here, however, that having the whole of "renewable energy resources" represented in this analysis by biomass alone, is a significant model restriction. The main reason for this restriction is, as indicated above, availability of comparable and replicable data, whereas, under other circumstances, this supply category should, of course, include deep geothermal potentials, solar thermal potentials, as well as other replenishable ambient resources. To still provide a visual indication of existing deep geothermal potentials, Figure 5 presents a map of the temperature distribution at 2000 meters depth, elaborated on the basis of Plate 3 in [59], which is reproduced from a previous WP2 deliverable report (D2.2).

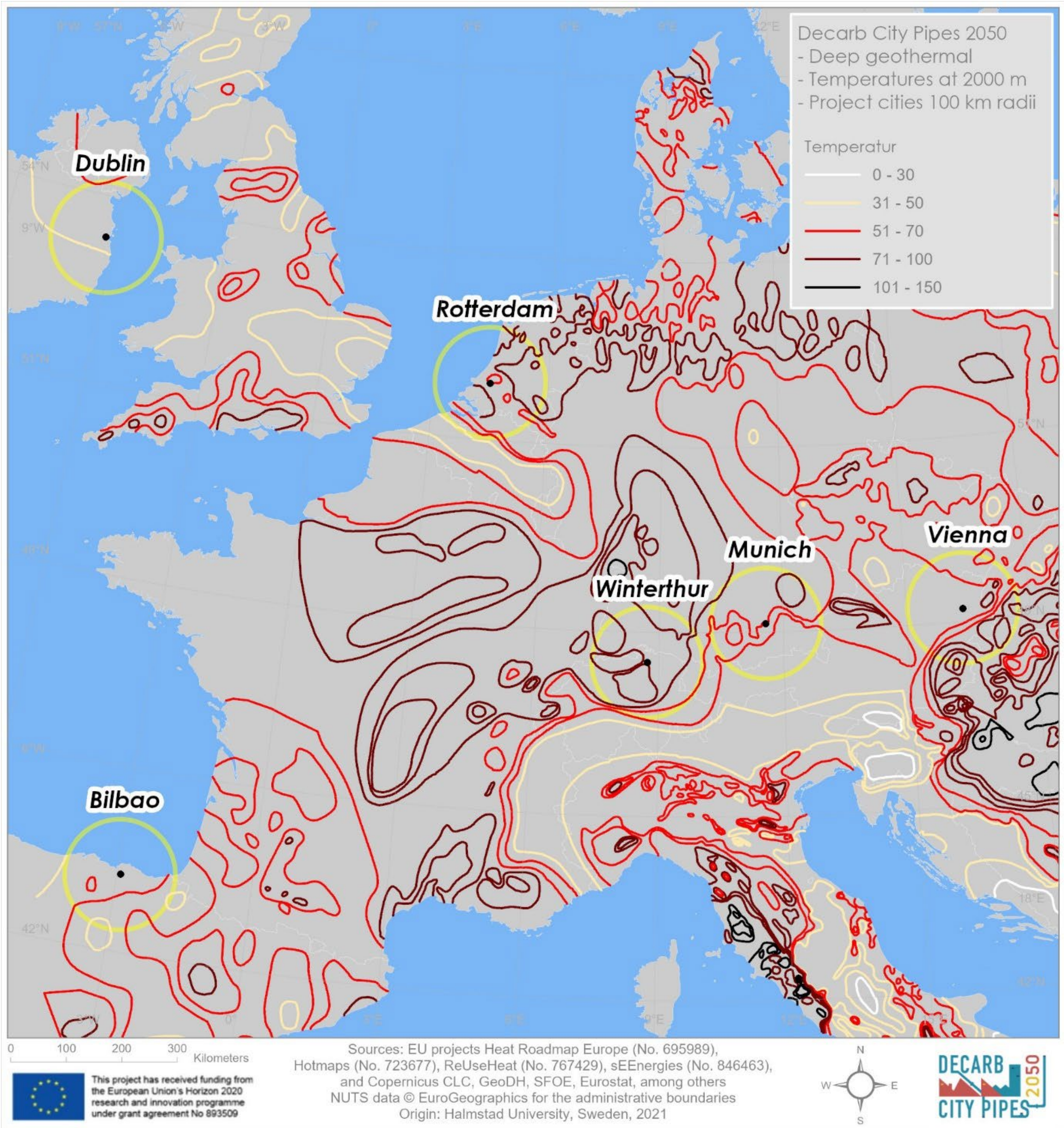


FIGURE 5. DEEP GEOTHERMAL TEMPERATURE DISTRIBUTION AT 2000 METER S DEPTH (˚C) WITH SIX OF THE SEVEN PROJECT CITIES OUTLINED BY CIRCLES. SOURCE: OWN ELABORATION OF PLATE 3 MAP IN [59].

As for the third side of the main criteria triangle, energy efficiency, the analysis should take into consideration all three sides of the problem. This is why the ten structuring criteria were defined, and the overall performance of each city regarding them is searched for.

3.2. City data for Baseline 2050 scenario

In this subsection, the objective is to present the seven project cities in more detail and with particular focus on the derived values of the ten structuring criteria for each respective city. While the ten structuring criteria themselves are rigorously defined, as outlined in Table 3 above, the following presentation distinguishes, for the purpose of transparency and elucidation, between those underlying raster data[11] which refers to, on the one hand, the 2050 baseline scenario (BL2050), and, on the other, to the 2050 frozen efficiency scenario (FE2050)[12]. For the sake of report disposition and readability, all graphs and map images relating to the latter have been located in appendix section 8.1, while all corresponding graphs and map images presented in this subsection refer to the former. In alphabetical order then, the Spanish city of Bilbao is the first of our seven project cities to now get further acquainted with.

3.2.1. Bilbao

As can be seen in the top map image of Figure 6 below, Bilbao is located in a valley by the Atlantic coast surrounded by higher ground and mountainous areas. The city has ocean access by the sea port and neighbours several other cities located in its direct vicinity. From the map it is directly observable that the city of Bilbao in its entirety, and not just selected parts of it, is characterised by coherent high levels of heat demand densities, or put differently, future annual heat demands for space heating and domestic hot water preparation in residential and service sector buildings in Bilbao are expected to be characterised by high levels of spatial concentration in the BL2050 projection (and, naturally, even more so under the FE2050 projection, as illustrated in the matching top map for Bilbao presented in annex Figure 30).

Figure 6 further provides an illustration of the city about three of the structuring criteria. These include heat demand density (at the top), distribution capital cost for district heating as a measure of structural energy efficiency (in the centre), and anticipated city population change between the years 2050 and 2015 (at the bottom). As the figure shows, there are many areas inside the city centre that have more than 3000 GJ/ha heat demand density (>830 MWh per hectare and year), thus very suitable for deploying district heating systems. This high-density level is maintained coherently throughout most of the urban area and is only marginally diminished when approaching the urban area's boundaries. There are also many areas within the city where the distribution capital cost for expanding district heating is reasonable. The point is that in many places with high heat demand density, the capital cost is low, and this is very advantageous when developing district heating. According to Figure 6, further, the population in most of the urban area will be dwindling by 2050, and the amount of this decrease is relatively high, more than 25% in many areas. This pattern is of importance not only in terms of H/C decarbonisation programs but in other urban planning issues as well. However, as illustrated in the annex bottom map (Figure 30), the relative population decrease is larger than the less ambitious relative heat demand reduction.

[11] The underlying raster data categories concerned are heat demand densities and distribution capital costs for district heating, as well as supplementary categories derived on the basis of these.

[12] For the sake of clarity, the sEEnergies Baseline 2050 scenario (BL2050) was created in principle to replicate the PRIMES baseline projection for 2050, which includes measures in line with the 2030 policy package for EU and thereafter Business-as-Usual from 2030 to 2050 [60, 61], whereas the sEEnergies Frozen Efficiency 2050 scenario (FE2050) was created to represent a less ambitious energy saving projection accounting only energy efficiency measures as achieved by contemporary actions and legislation.

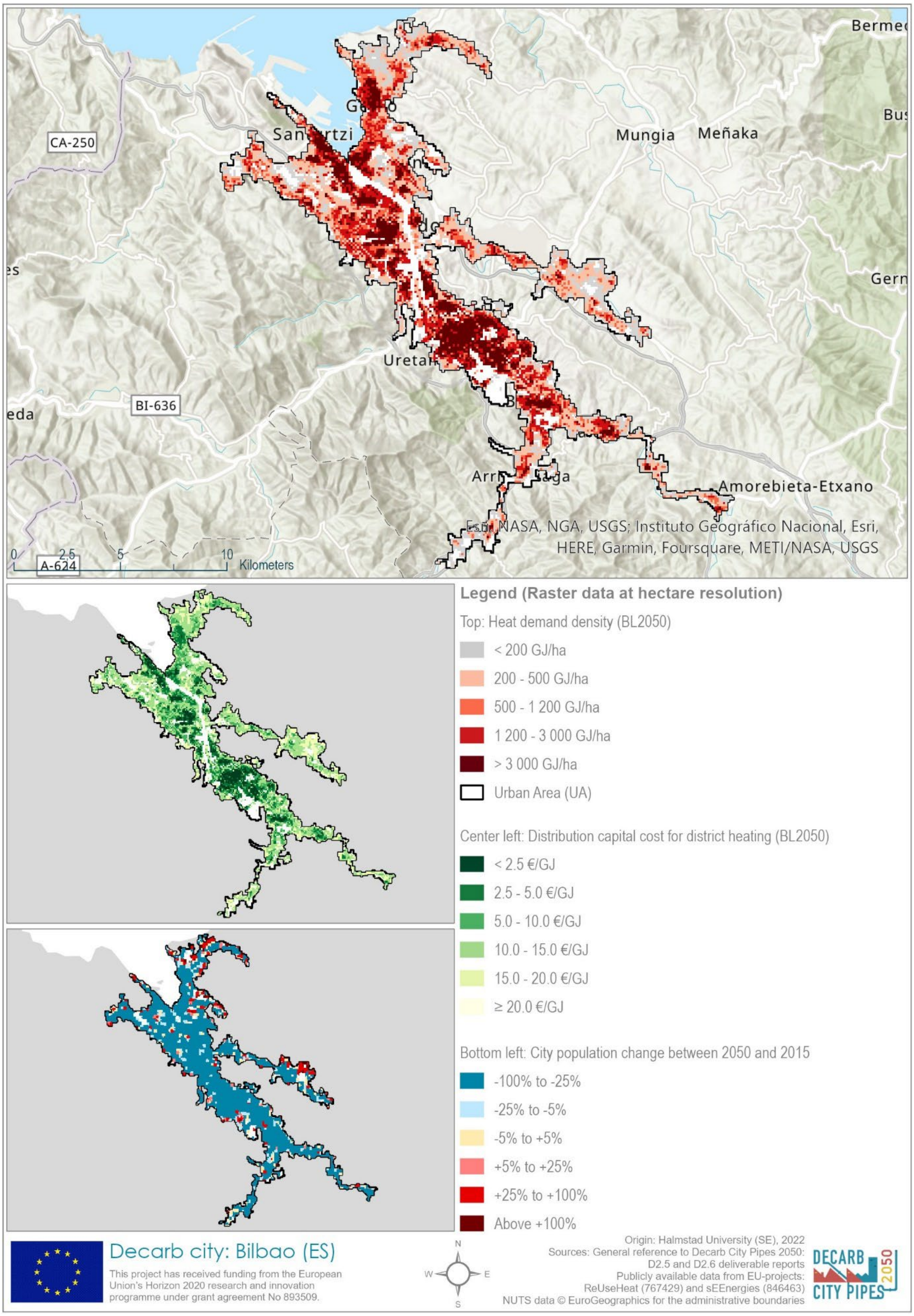


FIGURE 6. BILBAO MAP OVERVIEW 1: HEAT DEMAND DENSITY IN 2050 (BASELINE), DISTRIBUTION CAPITAL COST FOR DISTRICT HEATING IN 2050 (BASELINE), AND RELATIVE CHANGE IN CITY POPULATION BETWEEN 2050 AND 2015. SOURCES: [27, 44, 46, 50].

The condition of the city regarding each of the ten structuring criteria is presented in Table 6. The table also shows the average for the participating cities ("DCP2050 average", excluding Winterthur where no data was available, otherwise including Winterthur in the average), which affords a source for making comparisons and providing interpretation. The most crucial point in the table is that the city of Bilbao has no district heating coverage yet. This is an outstanding consideration when prospecting decarbonisation design approaches because developing a green heating system from scratch can be thought of.

Another important concern in respect, however, could be the lower-than-average levels of renewables and waste heat potentials. Nevertheless, a relatively high structural energy efficiency could make the situation trade-off in favour of developing CO_2-neutral H/C systems. Another critical issue is the high reliance of fossil fuels in the city's current heating and cooling sector. Diminishing the contribution of fossil fuels while the available renewable waste heat sources are not substantial would be a serious challenge. Still, regarding the anticipated waste heat potential, although lower than average in relative terms, a waste heat quotient (related to the BL2015 total city heat demand at 14.2 PJ/a, as shown in Table 5 above) of 0.58 is second, among the project cities, only to Rotterdam at a staggering ratio of 4.38.

TABLE 6. BILBAO CITY DATA FOR THE TEN STRUCTURING CRITERIA AND ASSOCIATED AVERAGE VALUES FOR THE SEVEN DCP2050 CITIES

Structuring criteria	Bilbao	DCP2050 average
City population	-34%	-6%
Heating index	71	97
Heat Demand Density	41%	37%
Individual energy efficiency	1.0	3.8
Structural energy efficiency	86%	57%
Dependency on fossil fuels	90%	64%
Potential for renewable sources	41.7	80.5
Potential for waste heat	8.3	13.7
Development of the built environment	16%	21%
Coverage of district heating	0%	25%

Complementary to the raster data maps presented in Figure 6 (Bilbao map overview 1) and Figure 30 (Bilbao map overview 3), feature data for point sources and regions are presented in Figure 7 (Bilbao map overview 2). As indicated above, the potential for renewable energy sources (on top) is here represented by that of biomass, where the JRC Enspreso 2050 reference scenario data, quantified by main sectors forestry, agriculture, and wastes, for 17 main energy commodities, and by NUTS2 regions, were apportioned[13] to the city by 50 and 100 km distances to the urban area's centre. As can be observed, the biomass potential within 100 km is around four times that within 50 km, as the area is quadrupled but also depending on the assessed potentials in the neighbouring regions. This result may denote that there are likely distances between source and demand points for H/C systems using regional biomass resources, as well as a natural competition with nearby cities. It is also noteworthy that this situation is the same for almost all of the project cities.

[13] Apportioning is a process in spatial analysis where attributes of an input polygon layer (in this case the biomass potentials by NUTS2 regions feature dataset) are summarised (proportionally) based on the spatial overlay of a target polygon layer (in this case the 50 km and 100 km circle datasets).

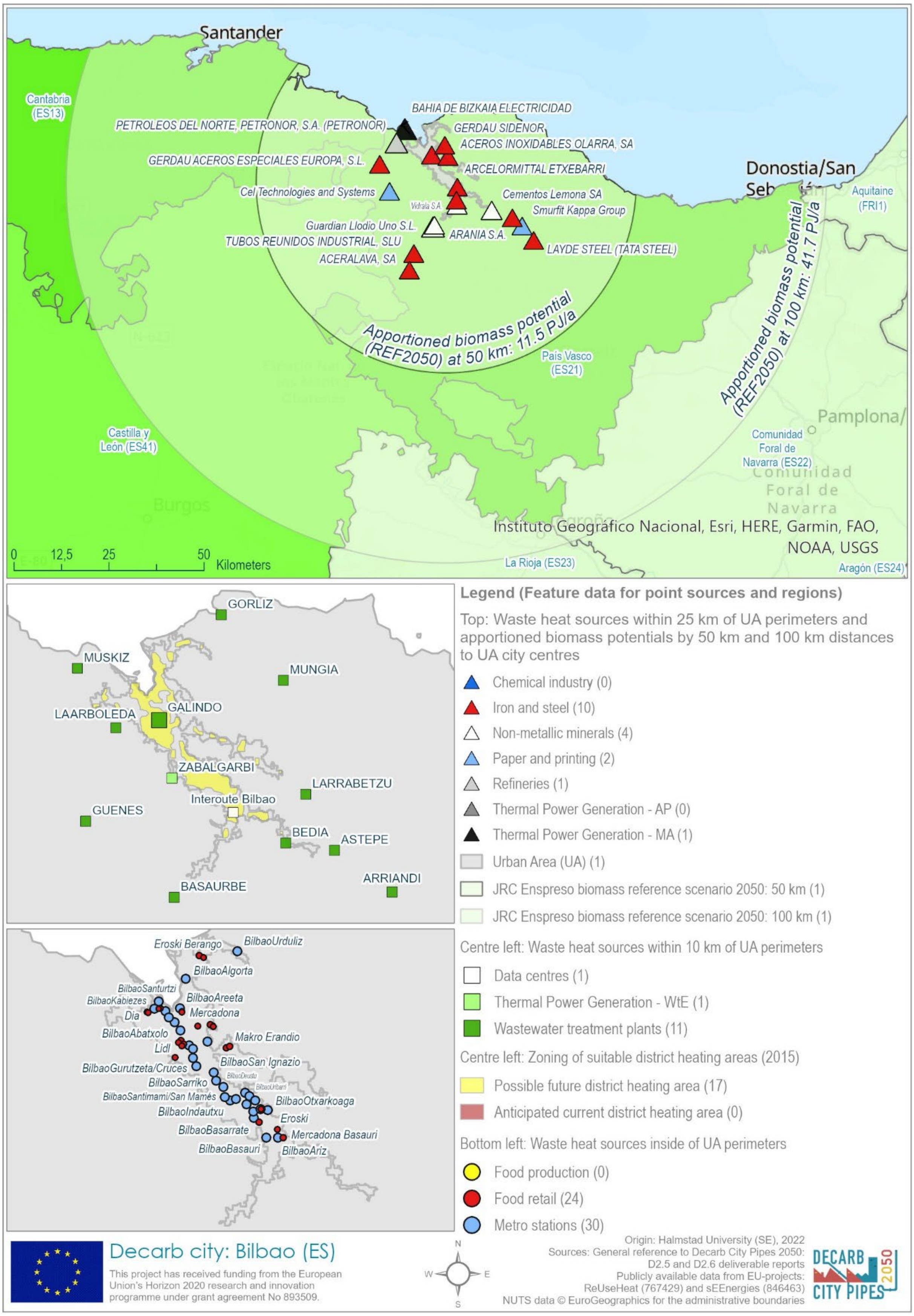


FIGURE 7. BILBAO MAP OVERVIEW 2: 2050 BIOMASS POTENTIALS (JRC ENSPRESO REFERENCE SCENARIO) APPORTIONED BY 50 KM AND 100 KM DISTANCES TO CITY CENTRE, WASTE HEAT SOURCES INSIDE, WITHIN 10 KM, AND WITHIN 25 KM OF UA'S PERIMETER, AND ZONING OF SUITABLE DISTRICT HEATING AREAS UNDER CURRENT CONDITIONS. SOURCES: [27, 34, 39, 43].

Figure 7 also shows (on top) that, within 25 kilometres of the urban area perimeters, iron and steel factories are the most frequent industrial units for waste heat sources in Bilbao, in addition to several other industries (non-metallic minerals, paper and printing etc.), one large-scale thermal power generation unit, and a refinery.

The maps in the centre and bottom of Figure 7 display the waste heat potentials within 10 km of, and inside of, the urban area perimeters respectively. There is one thermal power generation unit (waste incineration) and one data centre inside the urban area, but – keeping in mind that the underlying data for waste heat sources refer to current conditions in the context of this work – this could certainly be very different some thirty years from now. There also exist 11 waste water treatment plants, most of them in the inner city. Moreover, the city within its urban area enjoys food retailers and metro systems, which are examples of so-called unconventional waste heat sources possible to consider.

Another feature integrated into Figure 7 (middle map) is the outline of possible future district heating areas within the urban area, made feasible by use of an additional EU continental-wide dataset created in the sEEnergies project and made publicly available [39, 41]. Noteworthy, these possible district heating areas were established on the basis of current year heat demand densities (BL2015), which may serve as a reference for the calculated future year distribution capital costs presented in Figure 8 at left for the BL2050 scenario and in annex Figure 29 at left for the FE2050 scenario.

As can be seen at left in Figure 8, these distribution capital cost graphs have been designed in allegory with previously published accounts (see for example [9, 49, 62]), with cost curves indicating total heat market shares for district heating at corresponding specific cost levels. In the case of Bilbao, as expected given the overall high spatial concentration of heat demands, cost levels are generally low. In fact, up to 50-70% demand satisfaction by district heating are observable at comparably low marginal distribution capital cost levels.

The right-hand side plot in Figure 8 presents the distribution of total city heat demands by five heat demand density classes, comparing the base year 2015 and BL2050. Notably, the share of higher demand density classes (in particular, above 300 TJ/km^2) are decreasing by 2050. Accordingly, some areas that currently have very high heat demand densities, can be expected to be somewhat less dense under more ambitious energy saving scenarios.

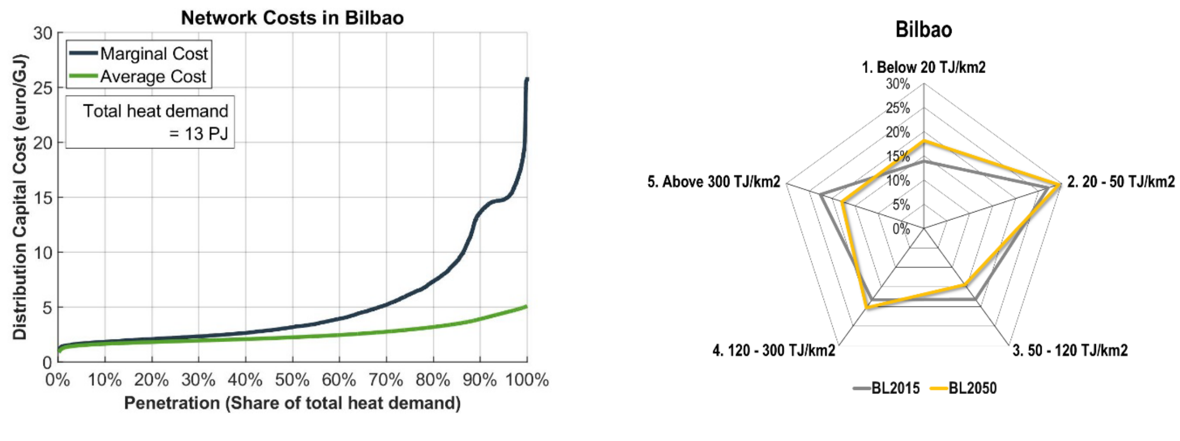


FIGURE 8. MARGINAL AND AVERAGE DISTRIBUTION CAPITAL COST LEVELS AND THE CORRESPONDING DISTRICT HEAT MARKET SHARES IN BILBAO FOR BL2050 [€/GJ] (LEFT). COST LEVELS REFLECT COSTS FOR BOTH DISTRIBUTION AND SERVICE PIPES. AT RIGHT, RADAR DIAGRAM WITH RELATIVE SHARES INDICATING THE DISTRIBUTION OF TOTAL CITY HEAT DEMAND BY FIVE HEAT DEMAND DENSITY CLASSES (CURRENT YEAR INCLUDED FOR REFERENCE (BL2015)).

3.2.2. Bratislava

Bratislava, the capital and the largest city of Slovakia, with a metro-area population over 430,000 residents, is located in southwestern Slovakia by the banks of the river Danube and the left bank of the river Morava, as outlined in the top map of Figure 9 (Bratislava map overview 1). The city is the easternmost one among the seven project cities and may be characterised by climate conditions which includes seasonal changes in cloudiness and sunshine duration.

Bratislava's status regarding the ten structuring criteria is presented in Table 7, once again with the average for the participating cities included for comparison and reference ("DCP2050 average", excluding Winterthur where no data was available, otherwise including Winterthur in the average). There are two indicators implying that the city is on a satisfactory path to heating and cooling decarbonisation. The first is that the current district heating coverage is 70%, which is considerably higher than the average. The second point strongly supporting decarbonisation is that the dependency of the city's heating and cooling systems on fossil fuels is relatively low among the cities[14]. On the downside, Bratislava's renewables and waste heat potentials are not so high, both below the mean.

TABLE 7. BRATISLAVA CITY DATA FOR THE TEN STRUCTURING CRITERIA AND ASSOCIATED AVERAGE VALUES FOR THE SEVEN DCP2050 CITIES

Structuring criteria	Bratislava	DCP2050 average
City population	-33%	-6%
Heating index	100	97
Heat Demand Density	41%	37%
Individual energy efficiency	-	3.8
Structural energy efficiency	47%	57%
Dependency on fossil fuels	30%	64%
Potential for renewable sources	51.2	80.5
Potential for waste heat	4.5	13.7
Development of the built environment	18%	21%
Coverage of district heating	70%	25%

The illustration of Bratislava regarding the baseline 2050 heat demand density (top), distribution capital cost for district heating (centre), and the city population change (bottom) is provided in Figure 9. As can be seen, there are a few rare areas with above 3000 GJ/ha heat demand density inside the urban region, but a dominance of areas with comparatively high heat demand density (between 500 and 3000 GJ/ha), which is reflected in a richer presence of medium range network cost levels. On the topic of the projected population, the overall decreasing trend is recognizable, although some parts in the north and northwest would experience more residents during the following decades. Considering the top and bottom maps together reveals that areas with the expected increasing population will have low heat demand density, which is indicative of urban sprawl by single-family settlements.

[14] It should however be noted that there is some ambiguity in the used input data on this point: the city´s energy mix in H/C is reported to consist of "Gas 30%" and "DH 70%", without any further explication of what actual fuels are used in the DH supply. It is not unlikely that considerable amounts of fossil fuels do contribute to the supply of a 70% DH heat market share, although this is only speculation (it is beyond the study scope to investigate this issue further). This might still serve as a useful example of the common confusion of district heating being treated as a "fuel" or "supply" when in fact it is a heat distribution infrastructure independent of used fuels and supply sources.

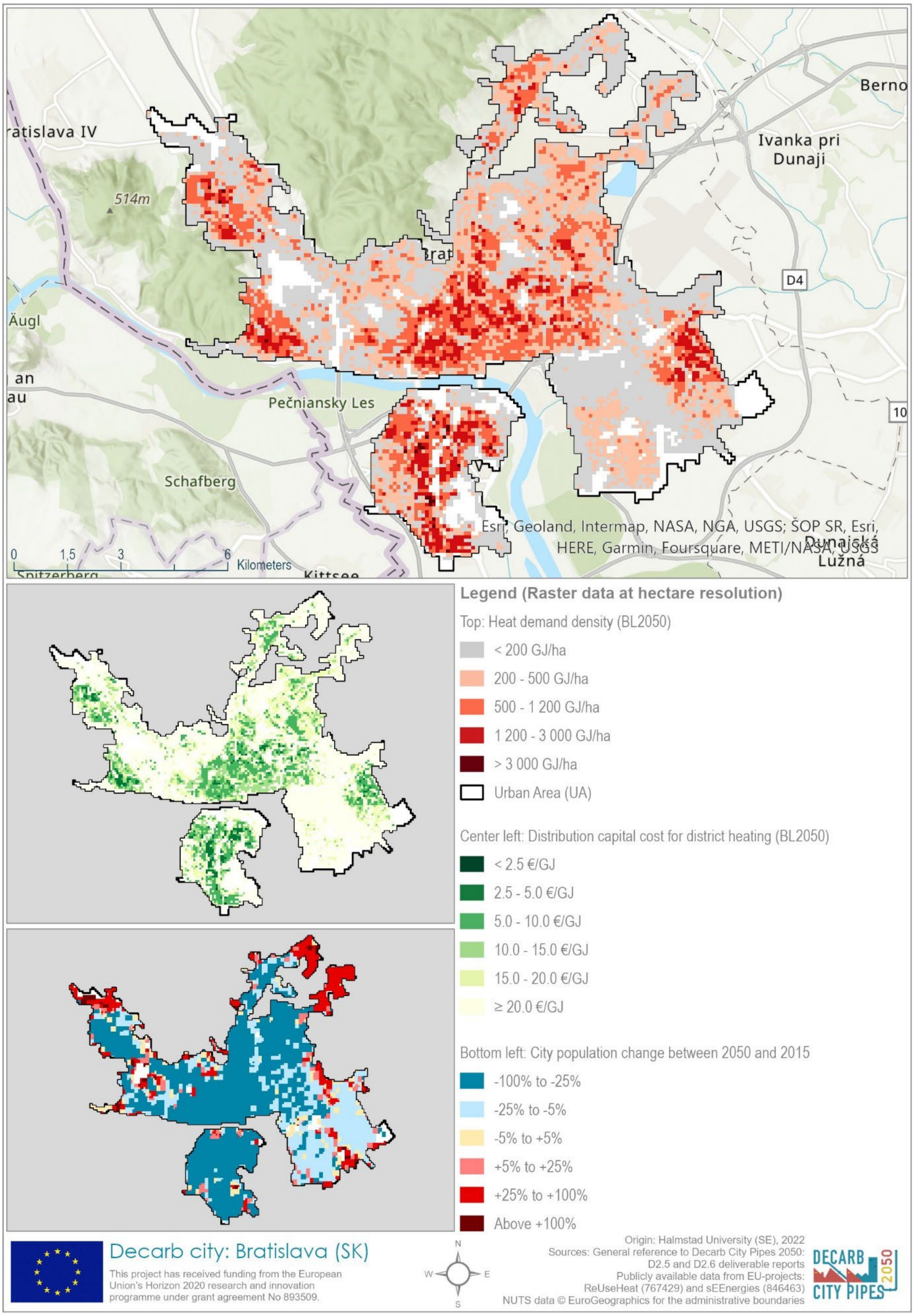
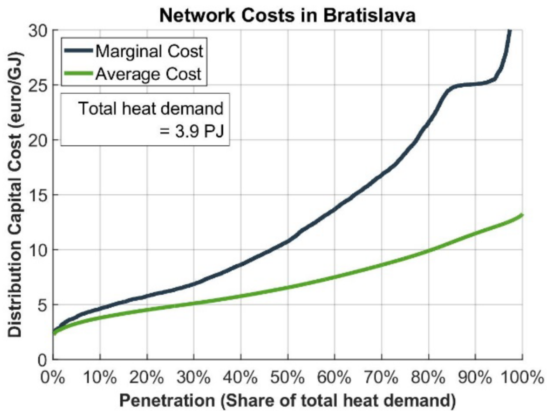


FIGURE 9. BRATISLAVA MAP OVERVIEW 1: HEAT DEMAND DENSITY IN 2050 (BASELINE), DISTRIBUTION CAPITAL COST FOR DISTRICT HEATING IN 2050 (BASELINE), AND RELATIVE CHANGE IN CITY POPULATION BETWEEN 2050 AND 2015. SOURCES: [27, 44, 46, 50].

Figure 10 shows the correlation of the city's distribution capital cost with the district heating market diffusion (on the left) and the total city heat demand distribution by heat demand density classes (on the right), here for the BL2050 scenario and in annex Figure 32 for the FE2050 scenario. As a consequence of medium level heat demand densities dominating the city's heat market, as well as by the above-mentioned tendencies towards urban sprawl, both marginal and average distribution capital costs are increasing relatively sharp in association with increases in district heating penetration. Compared to Bilbao, where 50% heat market shares are anticipated at marginal cost levels well below 5 euro/GJ (equivalent to some 18 euro/MWh) under this scenario, as outlined in Figure 8 above, similar market shares in Bratislava are expected at doubled cost levels (~10 euro/GJ, or ~36 euro/MWh). The radar diagram at right in Figure 10 reveals that one of the drivers for this situation, once again, is the clear shift towards less dense settlement areas within the city's urban area according to this projection. To still harvest opportunities for decarbonisation by structural energy efficiency under such conditions, it would be adequate to direct dedicated focus to low-temperature heat distribution technologies in conjunction with low-energy buildings.



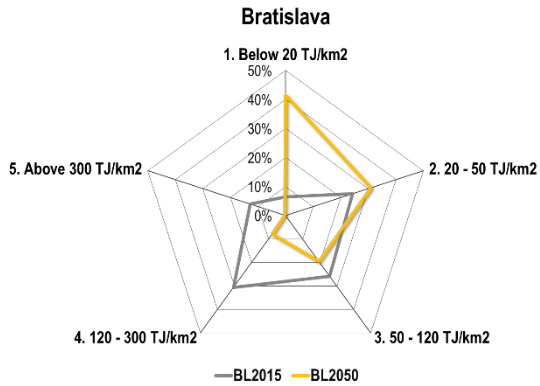


FIGURE 10. MARGINAL AND AVERAGE DISTRIBUTION CAPITAL COST LEVELS AND THE CORRESPONDING DISTRICT HEAT MARKET SHARES IN BRATISLAVA FOR BL2050 [€/GJ] (LEFT). COST LEVELS REFLECT COSTS FOR BOTH DISTRIBUTION AND SERVICE PIPES. AT RIGHT, RADAR DIAGRAM WITH RELATIVE SHARES INDICATING THE DISTRIBUTION OF TOTAL CITY HEAT DEMAND BY FIVE HEAT DEMAND DENSITY CLASSES (CURRENT YEAR INCLUDED FOR REFERENCE (BL2015)).

As for feature data, Figure 11 demonstrates the considered renewable and waste heat potentials for Bratislava and its near vicinity. It can be seen in the top map that about 15.5 PJ/a of biomass potential is available within 50 km of the city, while the potential will be more than 51 PJ/a if the boundary is expanded to 100 km. Regarding waste heat sources within a distance of 25 kilometres, one refinery and three thermal power generation plants appear to be in operation. In addition, as the middle map shows, 11 data centres, nine wastewater treatment plants, and one incineration power generation unit are operating within 10 km. Among other waste heat sources, one food production unit and 43 food retailers deserve to be mentioned, all are located inside the inner city, low temperature waste heat sources that would become more feasible to exploit in association with a dedicated development of low-temperature networks. Despite the availability of these sources, the city's waste heat potential is not considerable compared to the other cities. In terms of a waste heat ratio, as discussed above for Bilbao and Rotterdam, the corresponding quotient for Bratislava would be 0.38 under current year conditions (4.5 PJ/a of assessed waste heat potential divided by the annual BL2015 heat demand at 11.8 PJ, see Table 5). Noteworthy, if instead relating to the anticipated BL2050 heat demand (3.9 PJ), the quotient increases to 1.15.

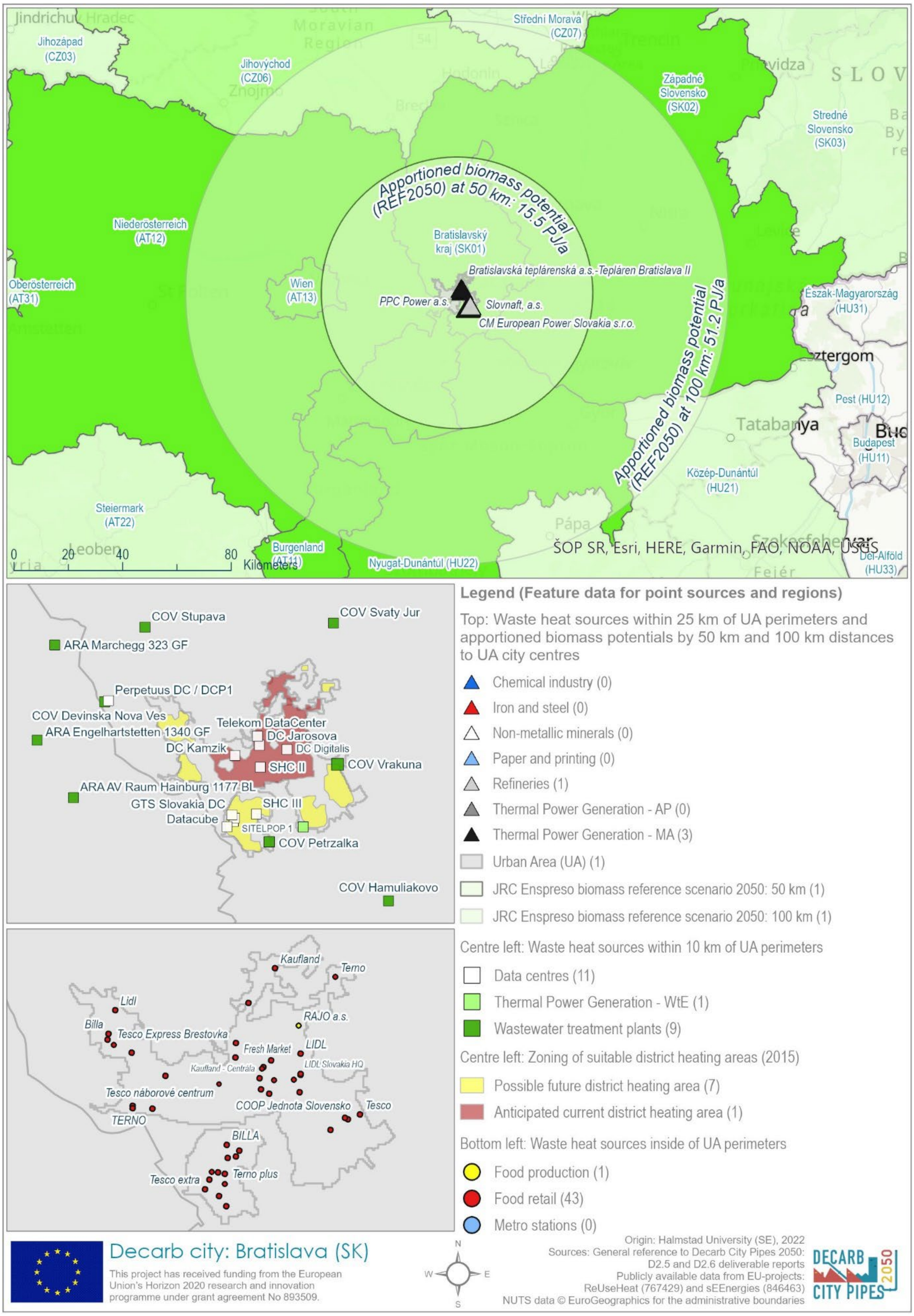


FIGURE 11. BRATISLAVA MAP OVERVIEW 2: 2050 BIOMASS POTENTIALS (JRC ENSPRESO REFERENCE SCENARIO) APPORTIONED BY 50 KM AND 100 KM DISTANCES TO CITY CENTRE, WASTE HEAT SOURCES INSIDE, WITHIN 10 KM, AND WITHIN 25 KM OF UA'S PERIMETER, AND ZONING OF SUITABLE DISTRICT HEATING AREAS UNDER CURRENT CONDITIONS. SOURCES: [27, 34, 39, 43].

3.2.3. Dublin

The city of Dublin, the Irish capital and, as with Bratislava, also the largest city in the country, is a coastal city hosting an urban population of approximately 1.34 million (2016) which is expected to decrease only marginally by 2050 (Table 8) and, as can be seen in the top map presented in Figure 12, which is further expected to predominantly live in moderately heat-demand dense settlements quite evenly distributed among the different city districts in the BL2050 scenario[15]. Apart from a few city centre areas with very high heat demand densities, that is densities in the order of 3000 GJ per hectare (~830 MWh/ha) and above, the majority of areas dedicated for housing should be associated with heat demand densities in the range from 500 GJ/ha to 1200 GJ/ha (or between some 140 MWh/ha to 335 MWh/ha).

Dublin's performance and relationship to the project city averages concerning the ten structuring criteria are presented in Table 8. Like Bilbao, the city does not benefit from district heating according to the used input data, although recent year developments, including the Tallaght District Heating Scheme[16] (the first large-scale Irish district heating system), are not represented in this data.

As for the city's dependency on fossil fuels, Dublin (together with Bilbao at 90%) represents the study maximum level at 89%, which is well above the project city average at 64%. The implication of the current dependency on oil and gas fuels, in combination with relatively low levels of both renewables and waste heat sources, translates into an essential need for concrete decarbonisation planning and careful choice of design approaches for the city, or, more precisely, careful choice of different design approaches for different neighbourhoods, districts, zones, and areas, within the city. Moreover, the city's below average heat demand density may denote that deploying district heating systems for the entire urban area would be rather expensive. Despite the city's low structural energy efficiency score, the high score on the individual energy efficiency metric (study maximum) is a promising opportunity for energy savings that the city can take advantage of on the road to decarbonisation.

TABLE 8. DUBLIN CITY DATA FOR THE TEN STRUCTURING CRITERIA AND ASSOCIATED AVERAGE VALUES FOR THE SEVEN DCP2050 CITIES

Structuring criteria	Dublin	DCP2050 average
City population	-2%	-6%
Heating index	98	97
Heat Demand Density	18%	37%
Individual energy efficiency	8.0	3.8
Structural energy efficiency	22%	57%
Dependency on fossil fuels	89%	64%
Potential for renewable sources	18.6	80.5
Potential for waste heat	8.3	13.7
Development of the built environment	29%	21%
Coverage of district heating	0%	25%

[15] Annex Figure 34 (Dublin map overview 3) shows the corresponding map for the FE2050 scenario, which, due, on the one hand, to its similarity in terms of total volumes with the current year (FE2050 heat demand at 18.8 PJ/a, BL2015 heat demand at 18.7 PJ/a, as outlined in Table 5), and, on the other, due to the principal status quo between the two year settings regarding heat demand density distribution within the five elaborated heat demand density classes (as illustrated by the radar diagram in annex Figure 33 at right), may be regarded as an acceptable approximation of the current heat demand density distribution in the city.

[16] (2022-10-28): https://www.codema.ie/projects/local-projects/tallaght-district-heating-scheme

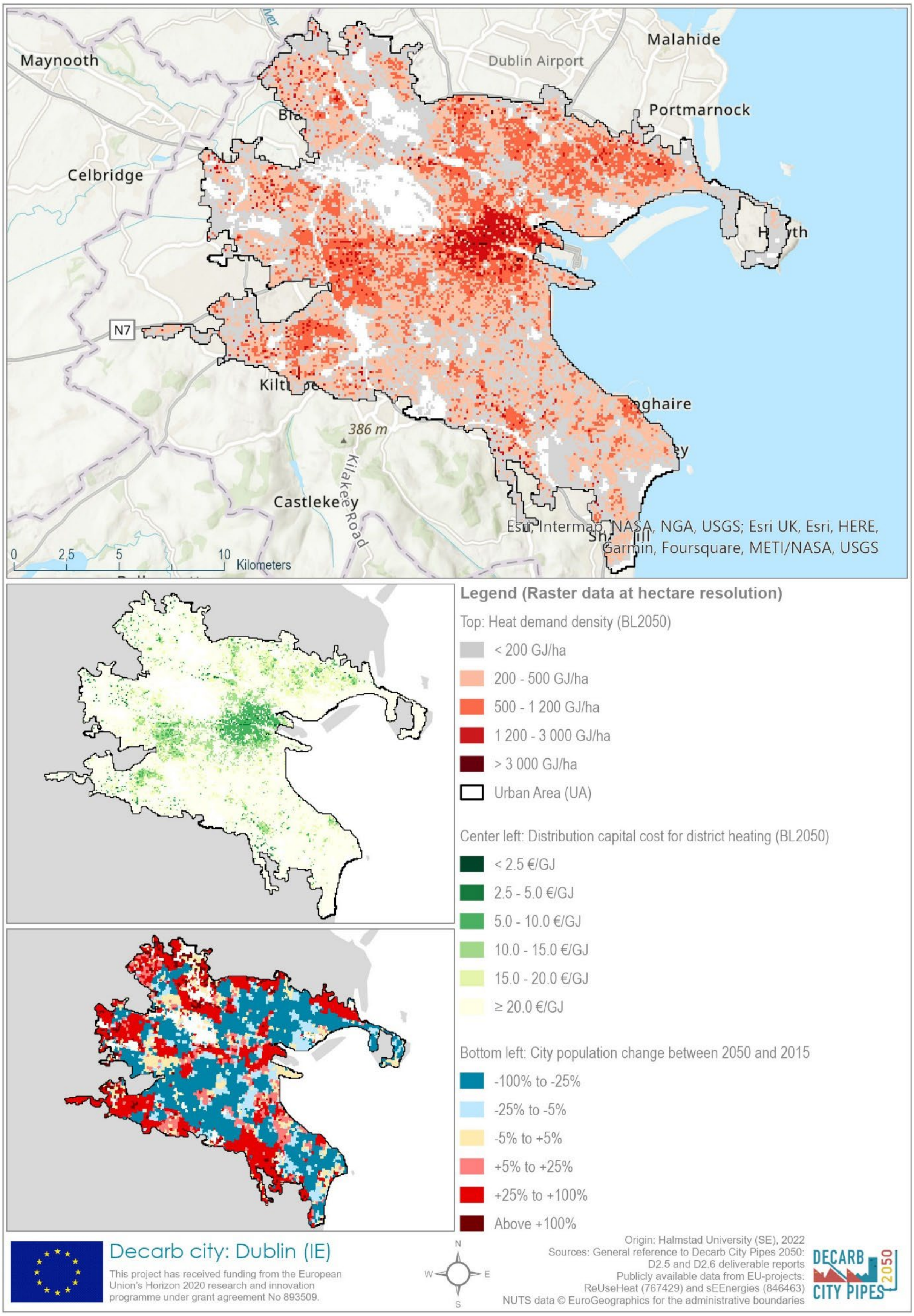


FIGURE 12. DUBLIN MAP OVERVIEW 1: HEAT DEMAND DENSITY IN 2050 (BASELINE), DISTRIBUTION CAPITAL COST FOR DISTRICT HEATING IN 2050 (BASELINE), AND RELATIVE CHANGE IN CITY POPULATION BETWEEN 2050 AND 2015. SOURCES: [27, 44, 46, 50].

Returning to the Figure 12 maps of the city in relation to the BL2050 heat demand density, the distribution capital cost for district heating, and the city population change, it is further observable in the top map that, under the more ambitious baseline 2050 scenario energy saving projection, very high heat-demand areas are quite few. Counteracting this tendency however is the positive attribute, at least from a perspective of economically justifying increased utilisation of district heating systems in the city, that most of the relatively high heat demand density areas (between 1200 and 3000 GJ/ha) are located close together in a region. This denotes that heat demand densities, at least in some parts of the city (mainly on the east coast), should be high enough for feasible network heat distribution also under an ambitious energy saving strategy, but also, that deliberate densification within residential and service sectors may be considered by the city administration as a relevant additional dimension in such a strategy.

The middle map in Figure 12 confirms the above analysis as it shows that the distribution capital cost (and synonymously structural energy efficiency) is affordable mainly on the east coast. The bottom map in the figure reveals, as observed also for Bratislava under this scenario, an uneven expected population expansion within the city with tendencies towards urban sprawl (quite the opposite of dedicated densification). While there are many places where in excess of a 25% increase in population is anticipated (mainly in the outskirts), there ironically exist numerous inner-city zones with over 25% reductions foreseen[17].

Figure 13 displays the city's distribution capital cost for district heating (on the left) and the distribution of the city heat demand by heat demand density classes (on the right) under the baseline 20050 scenario. The distribution capital cost rises quite fast with the district heating penetration rate in this projection (considerably faster than the corresponding FE2050 cost curve shown in annex Figure 33 at left).

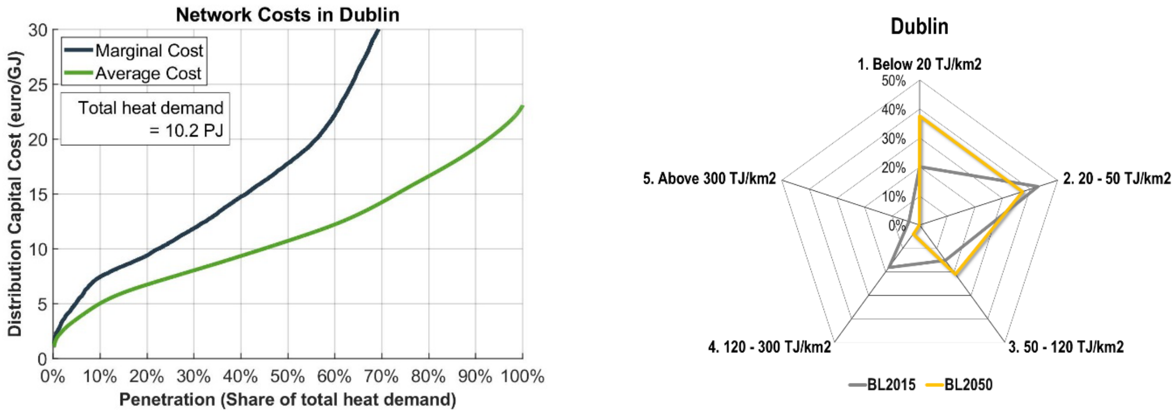


FIGURE 13. MARGINAL AND AVERAGE DISTRIBUTION CAPITAL COST LEVELS AND THE CORRESPONDING DISTRICT HEAT MARKET SHARES IN DUBLIN FOR BL2050 [€/GJ] (LEFT). COST LEVELS REFLECT COSTS FOR BOTH DISTRIBUTION AND SERVICE PIPES. AT RIGHT, RADAR DIAGRAM WITH RELATIVE SHARES INDICATING THE DISTRIBUTION OF TOTAL CITY HEAT DEMAND BY FIVE HEAT DEMAND DENSITY CLASSES (CURRENT YEAR INCLUDED FOR REFERENCE (BL2015)).

[17] Regarding the underlying data used here on the anticipated spatial distribution of future European populations, the sEEnergies "future population model", which rendered this data, utilises in essence a combination of *"… regional and national population forecasts and past local trends based on 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… the local increment is then adjusted to regional forecasts that include demographic dynamics, and finally anchored to the national forecasts*" (citations from section 2.1.2. Population development modelling, on page 19, in [49], a reference which also provides further reading and detail on model assumptions and limitations).

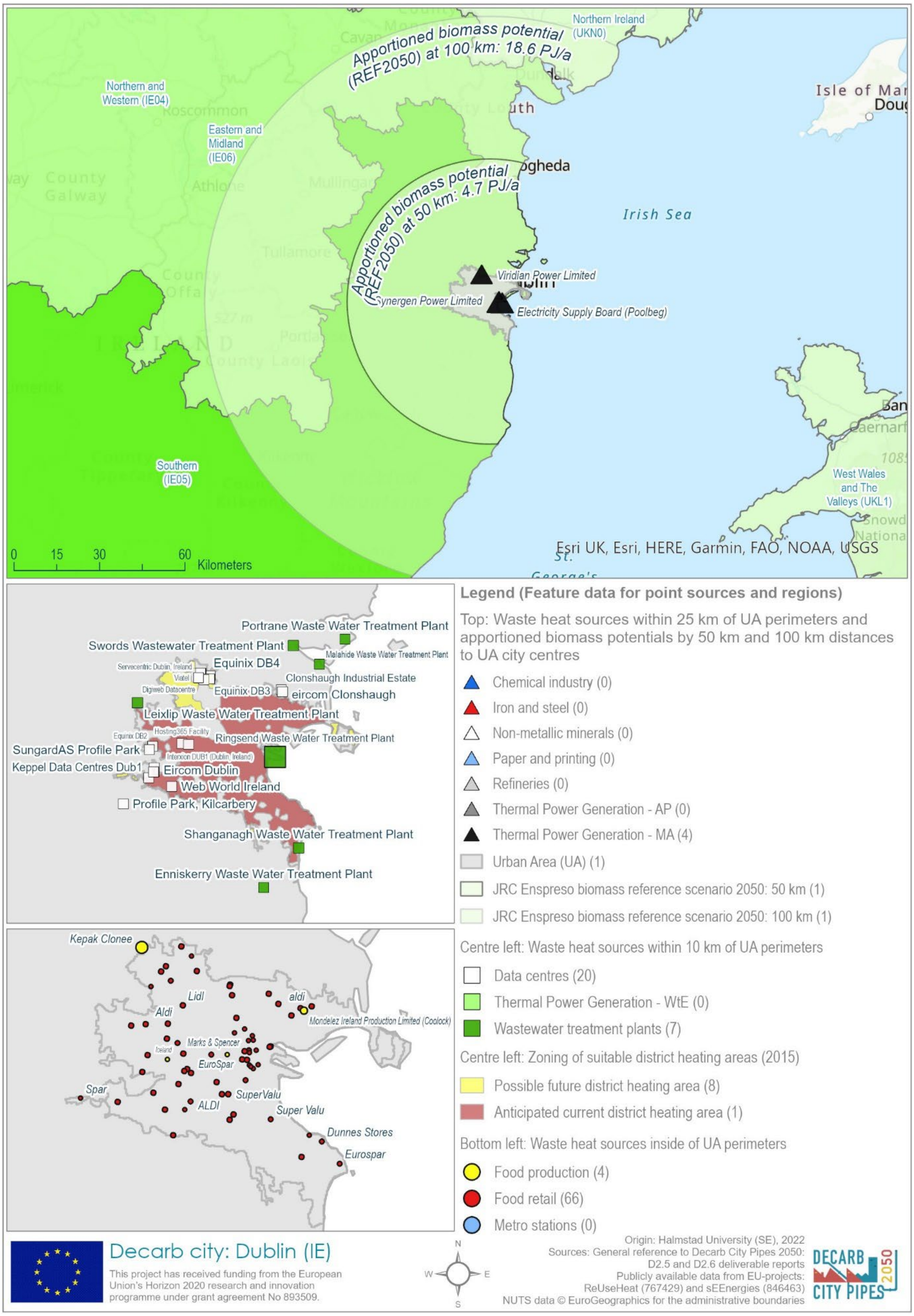


FIGURE 14. DUBLIN MAP OVERVIEW 2: 2050 BIOMASS POTENTIALS (JRC ENSPRESO REFERENCE SCENARIO) APPORTIONED BY 50 KM AND 100 KM DISTANCES TO CITY CENTRE, WASTE HEAT SOURCES INSIDE, WITHIN 10 KM, AND WITHIN 25 KM OF UA'S PERIMETER, AND ZONING OF SUITABLE DISTRICT HEATING AREAS UNDER CURRENT CONDITIONS (NOTE: ANTICIPATED CURRENT DH AREA NOT REPRESENTATIVE). SOURCES: [27, 34, 39, 43].

As also observable in Figure 13, at left, the average distribution capital cost for Dublin under the BL2050 scenario increases continuously with the penetration rate and reaches above 22 euro/GJ for 100% penetration, which is considered high in comparison with the other cities. The radar plot at right in Figure 13 provides additional evidence for the declining physical suitability[18] for district heating under this projection. As can be seen in the figure, there is a principal shift from the two highest density classes (in particular from density class 4: 120 – 300 TJ/km^2) towards the mid and low-density classes (in particular towards density class 1: Below 20 TJ/km^2), once again confirming the demographical tendencies commented upon above with reference to the bottom map in Figure 12.

As for renewable and waste heat sources in the Irish capital, Figure 14 displays the corresponding potential sources within the stipulated inside, within 10 km, 25 km, 50 km, and 100 km distances under consideration. Biomass potentials are present, but comparably low. Four thermal power plants can be seen inside the city, which of course represent rich opportunities for heat recoveries if practically viable (and still operational some 30 years from now?). Among other waste heat sources, the industrial option is remarkably inexistent inside or in the city's vicinity, while several wastewater treatment plants, some food production units, and plenty of food retailers are currently in operation within or around the city. Noteworthy, the city of Dublin hosts a large amount of data centres (waste heat from one of which the above-mentioned Tallaght system is already exploiting), and this emerging activity sector represents indeed a realistic and unique asset for the city. However, apart from this opportunity, and on the whole, the city cannot be described as particularly rich neither in renewable potentials nor in waste heat sources when compared with the other project cities (at least not in terms of the ten structuring criteria parameters investigated in this context).

3.2.4. Munich

Munich is the third-largest city in Germany and the capital and most populous city of the Bavaria state. Covering an area of 311 km^2, Munich has nearly 1.5 million inhabitants and is respected as quite dense. Located in south-eastern Germany, 500 meters above sea level, the city's climate is slightly continental, with cold winters and mild to pleasantly warm summers. The city aims to fulfil its power needs with green electricity by 2025. The primary use sector of energy in Munich households is heating, and the city has already focused on accelerated development of geothermal energy projects to fully cover its district heating by renewables by 2040, as well as new ideas and solutions for a sustainable future city [63].

For our analysis, Figure 15 illustrates heat demand density (on top), distribution capital cost for district heating (centre), and population change (bottom) for Munich according to the baseline 2050 scenario projection. The figure reveals how dense the city really is (even more so under the less ambitious energy-saving scenario presented in annex Figure 36) and how many areas with above 3000 GJ/ha heat demand densities that exist – principally all of the inner city may in fact be characterised as very heat-demand dense, which, consequently, translates into a wide presence of low-cost conditions for district heating network investments. As for population change, moreover, all city neighbourhoods will experience population increases, in most cases in the order of 5% to 25% relative to current counts.

[18] The term "physical suitability" (for district hearing) was introduced as a synonym for heat demand density by Persson et al. in [9], a term accompanied by "economical suitability", thus synonymous with the distribution capital cost metric.

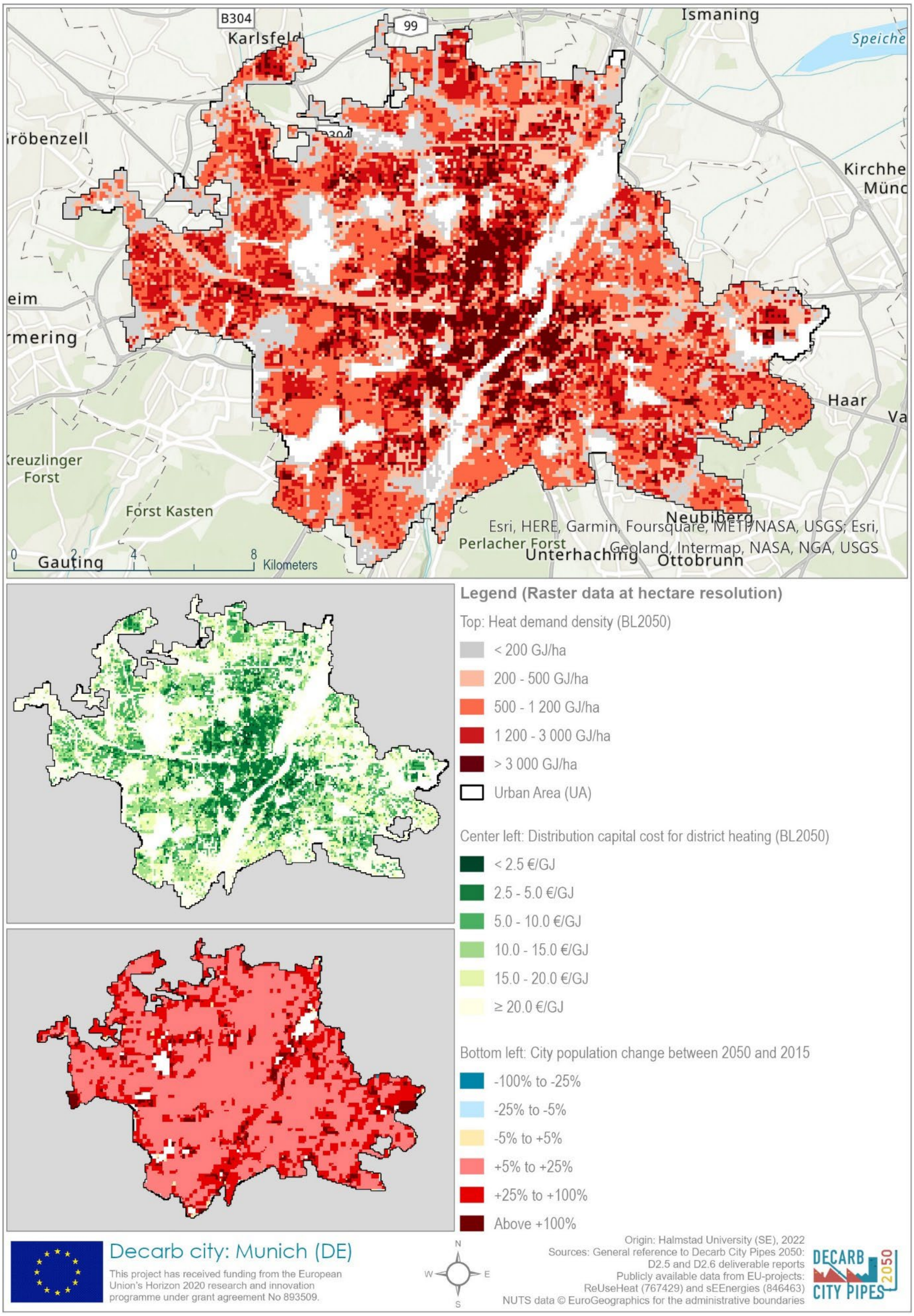


FIGURE 15. MUNICH MAP OVERVIEW 1: HEAT DEMAND DENSITY IN 2050 (BASELINE), DISTRIBUTION CAPITAL COST FOR DISTRICT HEATING IN 2050 (BASELINE), AND RELATIVE CHANGE IN CITY POPULATION BETWEEN 2050 AND 2015. SOURCES: [27, 44, 46, 50].

Table 9 provides an overview of Munich´s situation in terms of the ten structuring criteria and compares it with the cities' average. Two affirmative points that support H/C decarbonisation plans are that the city's potential for renewable sources is higher, and the current dependency of the city on fossil fuels is lower than the mean. In addition, the city's total heat demand density and its structural energy efficiency exceed the average. These characteristics are certainly in favour of sustaining green H/C systems. The note is that the city population is rising, which implies the likeliness as well of rising H/C demands in the city by 2050, in particular if related energy saving measures and other demand side management strategies are overlooked. Noteworthy, with a current 30% share of the city heat market, district heating is already an established and existing infrastructure in the city.

TABLE 9. MUNICH CITY DATA FOR THE TEN STRUCTURING CRITERIA AND ASSOCIATED AVERAGE VALUES FOR THE SEVEN DCP2050 CITIES

Structuring criteria	Munich	DCP2050 average
City population	27%	-6%
Heating index	108	97
Heat Demand Density	46%	37%
Individual energy efficiency	4.0	3.8
Structural energy efficiency	65%	57%
Dependency on fossil fuels	50%	64%
Potential for renewable sources	134.9	80.5
Potential for waste heat	8.7	13.7
Development of the built environment	7%	21%
Coverage of district heating	30%	25%

Figure 16 puts in view, for the BL2050 setting (corresponding FE2050 graphs in appendix Figure 35), the city's distribution capital costs for district heating (left) and the distribution of the city heat demand by heat demand density classes (right). It is observable that the average capital cost is stupendously reasonable even when contemplating the extreme case of the whole city heat demand being satisfied by district heating. The radar graph makes visible that the city, despite reductions in the two highest density classes, still manages to maintain large proportions of the demand at densities well above 50 TJ/km^2 in this scenario.

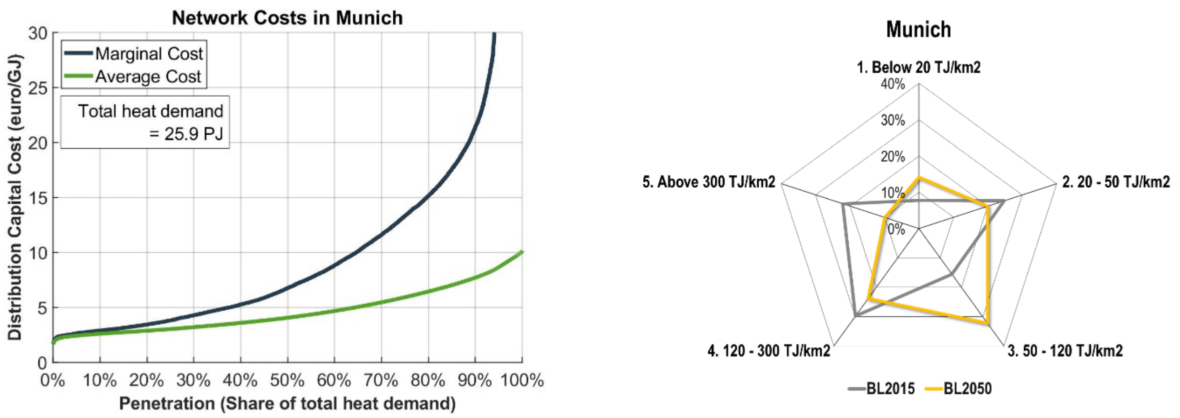


FIGURE 16. MARGINAL AND AVERAGE DISTRIBUTION CAPITAL COST LEVELS AND THE CORRESPONDING DISTRICT HEAT MARKET SHARES IN MUNICH FOR BL2050 [€/GJ] (LEFT). COST LEVELS REFLECT COSTS FOR BOTH DISTRIBUTION AND SERVICE PIPES. AT RIGHT, RADAR DIAGRAM WITH RELATIVE SHARES INDICATING THE DISTRIBUTION OF TOTAL CITY HEAT DEMAND BY FIVE HEAT DEMAND DENSITY CLASSES (CURRENT YEAR INCLUDED FOR REFERENCE (BL2015)).

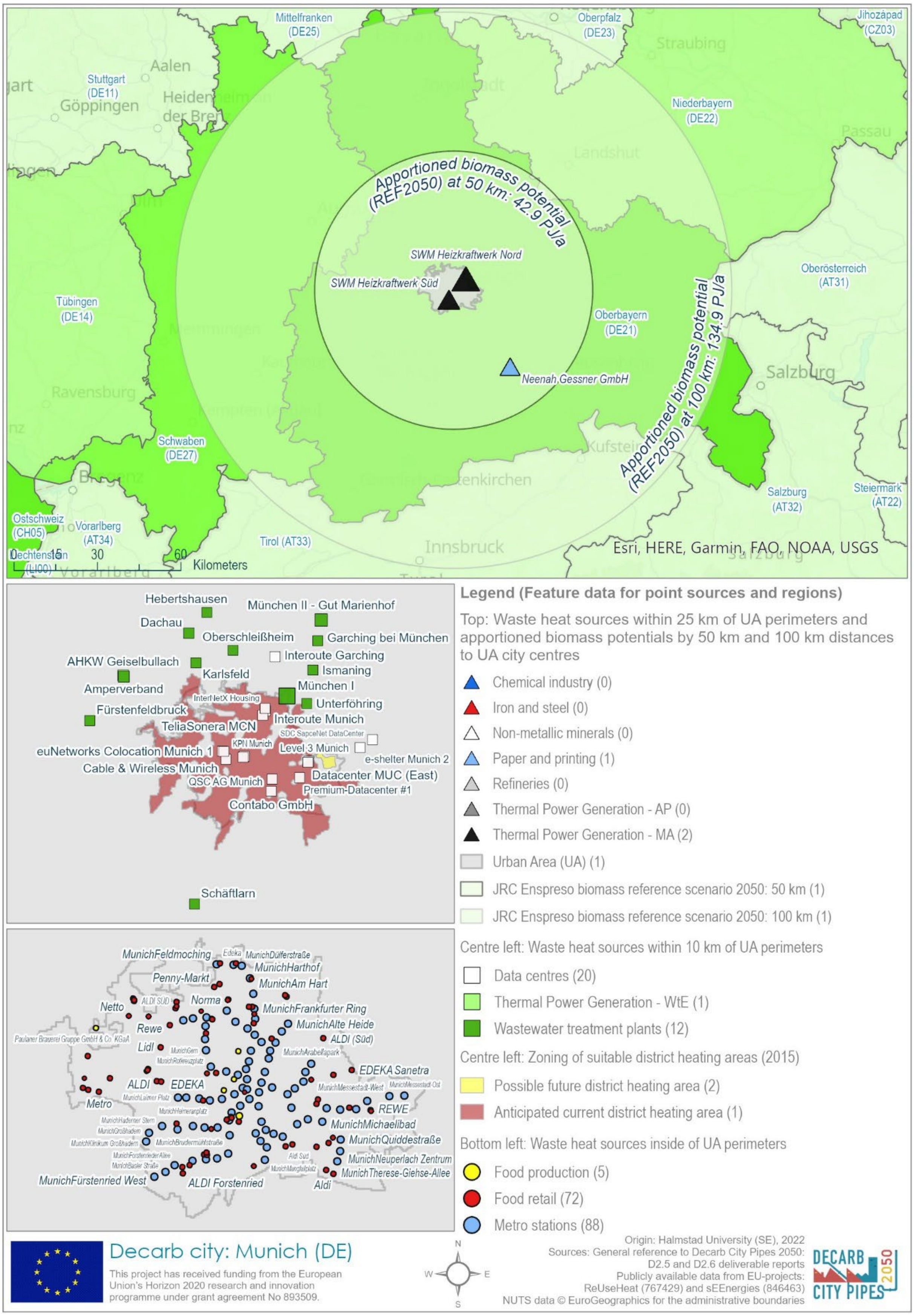


FIGURE 17. MUNICH MAP OVERVIEW 2: 2050 BIOMASS POTENTIALS (JRC ENSPRESO REFERENCE SCENARIO) APPORTIONED BY 50 KM AND 100 KM DISTANCES TO CITY CENTRE, WASTE HEAT SOURCES INSIDE, WITHIN 10 KM, AND WITHIN 25 KM OF UA'S PERIMETER, AND ZONING OF SUITABLE DISTRICT HEATING AREAS UNDER CURRENT CONDITIONS. SOURCES: [27, 34, 39, 43].

If, hypothetically, the city of Munich alone would enjoy sole access and exploitation right to regionally available biomass resources within a 100 kilometre radius from the city centre, as depicted in the top map of Figure 17, a total of 134.9 PJ (~37 TWh) would be available on an annual basis (according to the JRC Enspreso reference scenario, as further referenced in Table 1 above). Even at half the distance (at a 50 km radius distance), this renewable energy potential (at 42.9 PJ, or ~12 TWh) exceeds anticipated city heat demands under all considered study scenarios (see Table 5 above), which stands out as a fact that deserves explicit mentioning.

Despite it being a well-known circumstance in the contemporary discourse and debate on biomass, and its role in the green economy, that, firstly; it is a replenishable and “sustainable” resource only under proper and responsible management, and secondly; that it is a useful resource in many other activities and sectors, and therefore delicate, it should also be recognised that it is one of few combustible renewable sources, thus capable of high-temperature applications such as peak load heat supply in large-scale district heating systems during winter season cold spells. Now, while the biomass potential here outlined for Munich, as well as those outlined for the other project cities in this report, is partly imaginary, since in reality the city does not enjoy sole access but, according to the above, is, in fact, competing for the access to this resource both within its own internal activity sectors as well as with its external neighbours, it is partly real – and, as a matter of prioritisation, in particular if a – large – city decides on a H/C decarbonisation strategy which includes – large-scale – deployment of district heating, could come to very good use by such applications.

Among waste heat sources, as also presented in Figure 17, Munich benefits, among other, from two thermal electricity generation units and one paper and printing industrial site, one waste-to-energy power plant, and 12 wastewater treatment plants. Moreover, there are several data centres, food production plants, food retailers, as well as metro stations, inside the city that all represent rich opportunities for heat recycling.

3.2.5. Rotterdam

The top map in Figure 18 shows the urban area of Rotterdam north of the Nieuwe Maas channel. Since the urban area south of the channel initially was interpreted as mainly consisting of industrial areas (see footnote 9 above), this part of the city, despite being represented in the used input data, was regretfully omitted in this analysis. Apart from being an historic city, as well as the second largest municipality in the country, Rotterdam displays heat demand density features highly characteristic for Dutch towns and cities (similar to those, for example, also in the United Kingdom).

These characteristics, that is a bias towards mid-level to semi-high densities in urban areas, may be viewed as a result of widespread settlement structures consisting of densely built single-family house districts rather than sparsely built multi-family house districts (as are typical in some Baltic and Scandinavian countries). Despite being a city in one of the densest places in the world, in terms of built-up areas, Rotterdam is, ironically, a city with rather moderate concentration levels of building heat demands, which is observable also in the two future year projections of this study, i.e. in the top map of annex Figure 38 for the frozen efficiency 2050 scenario, as well as in the top map of Figure 18 for the baseline 2050 scenario projection. In both of these maps it may be seen that the occurrence of very low, or very high, heat demands densities are very rare, as mid-level densities clearly dominate.

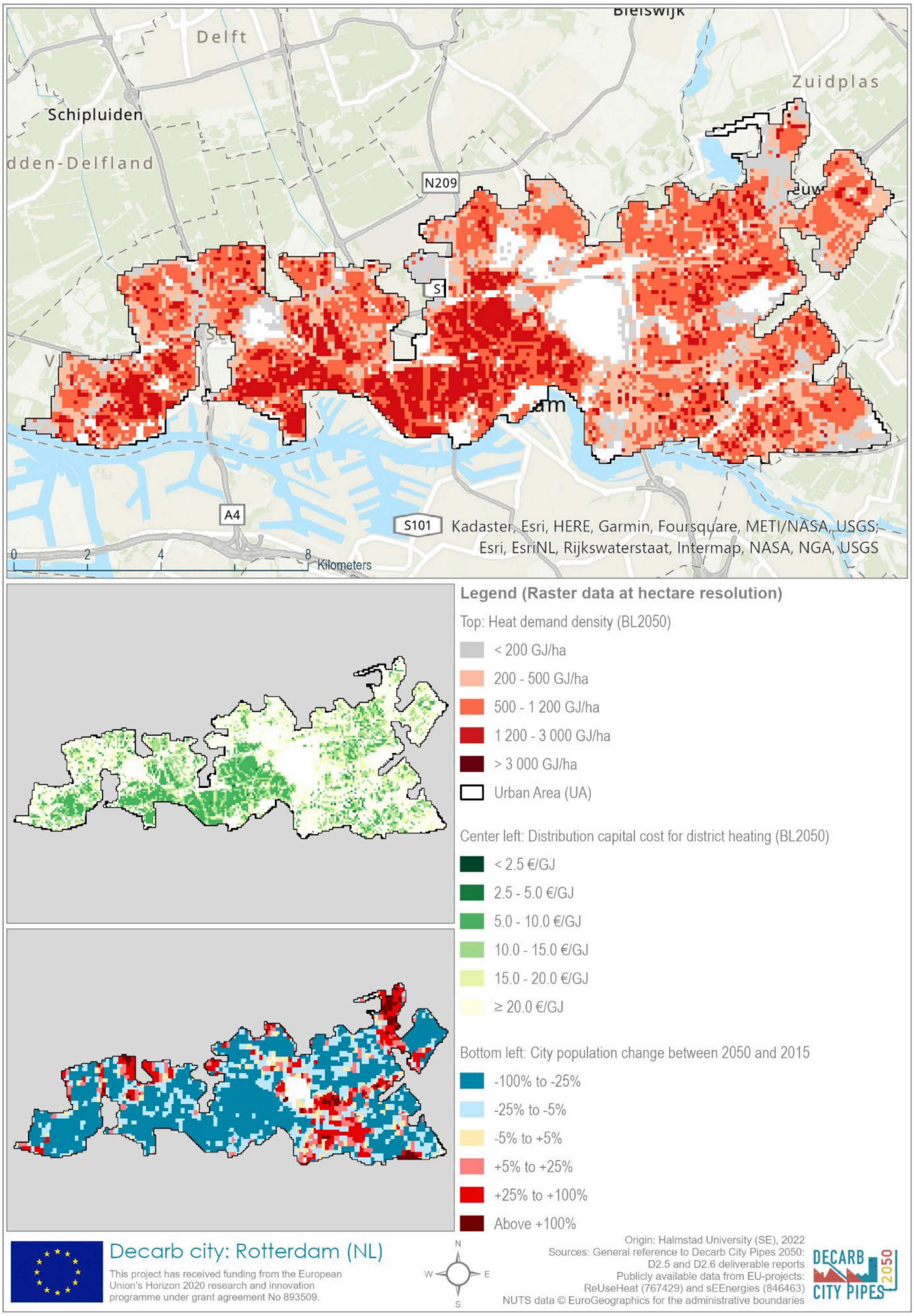


FIGURE 18. ROTTERDAM MAP OVERVIEW 1: HEAT DEMAND DENSITY IN 2050 (BASELINE), DISTRIBUTION CAPITAL COST FOR DISTRICT HEATING IN 2050 (BASELINE), AND RELATIVE CHANGE IN CITY POPULATION BETWEEN 2050 AND 2015. SOURCES: [27, 44, 46, 50]. LIMITATION NOTE: URBAN AREAS SOUTH OF THE NIEUWE MAAS CHANNEL NOT INCLUDED IN THE ANALYSIS.

As partly visible in the top map of Figure 18, Rotterdam also houses Europe's biggest seaport, which plays a key role for various trade activities and in supplying coal, gas, and biomass for North-western Europe. The city, with its heavy industrial profile, has also become a sort of feeding ground for new ideas and solutions regarding resource-efficient urban activities and settlements [64]. Accordingly, and as presented in Table 10 regarding the study data used for the determination of the ten structuring criteria for the city of Rotterdam, and as already indicated in the all-cities overview map presented above in Figure 4, the most notable metric for the city is its extremely high waste heat potential, found at some three times the study average (38.1 PJ, or some 11 TWh, annually). This itself is the most advantageous attribute of the city in view of H/C decarbonisation practices, and suggests, at least in view of any kind of large-scale recovery, decarbonisation strategies which will put appropriate heat distribution infrastructures in place for its distribution and reuse. See further the Rotterdam map overview 2 in Figure 19 for additional information and details on the unique waste heat potential in the city.

TABLE 10. ROTTERDAM CITY DATA FOR THE TEN STRUCTURING CRITERIA AND ASSOCIATED AVERAGE VALUES FOR THE SEVEN DCP2050 CITIES

Structuring criteria	Rotterdam	DCP2050 average
City population	-17%	-6%
Heating index	96	97
Heat Demand Density	30%	37%
Individual energy efficiency	3.0	3.8
Structural energy efficiency	41%	57%
Dependency on fossil fuels	72%	64%
Potential for renewable sources	62.1	80.5
Potential for waste heat	38.1	13.7
Development of the built environment	24%	21%
Coverage of district heating	18%	25%

As for the other nine structuring criteria, Table 10 also makes it clear that in most cases Rotterdam is often close to the mean. Exceptions from this includes the city's structural energy efficiency score, which is a bit lower than the average (and which principally relates to the above discussion on typical heat demand density “characteristics” for Dutch towns and cities), and its dependency on fossil fuels, which is slightly higher than the average.

A closer look at the city´s distribution capital cost for district heating and population change under the BL2050 scenario, as depicted in the middle and bottom maps of Figure 18 respectively, large segments of the urban area should have reasonably low distribution capital cost levels for feasible investments in district heating networks (also visible in the baseline cost curves shown in Figure 20 at left), albeit perhaps more seldom at straight-out lucrative conditions. Depending on the level of future energy savings, where, under less ambitious efforts to reduce end-use building heat demands (as in the FE2050 scenario illustrated in annex Figure 38), investments in structural energy efficiency measures should, in principle, become more profitable. As for Dublin, concerning the city population development towards 2050, dedicated densification strategies within the inner-city districts may prove relevant, since not only the overall number of inhabitants is expected to decrease (-17%, Table 10), in addition, there are indications of urban sprawl also in this city, with a general migration from inner to outer city areas anticipated in the used input data.

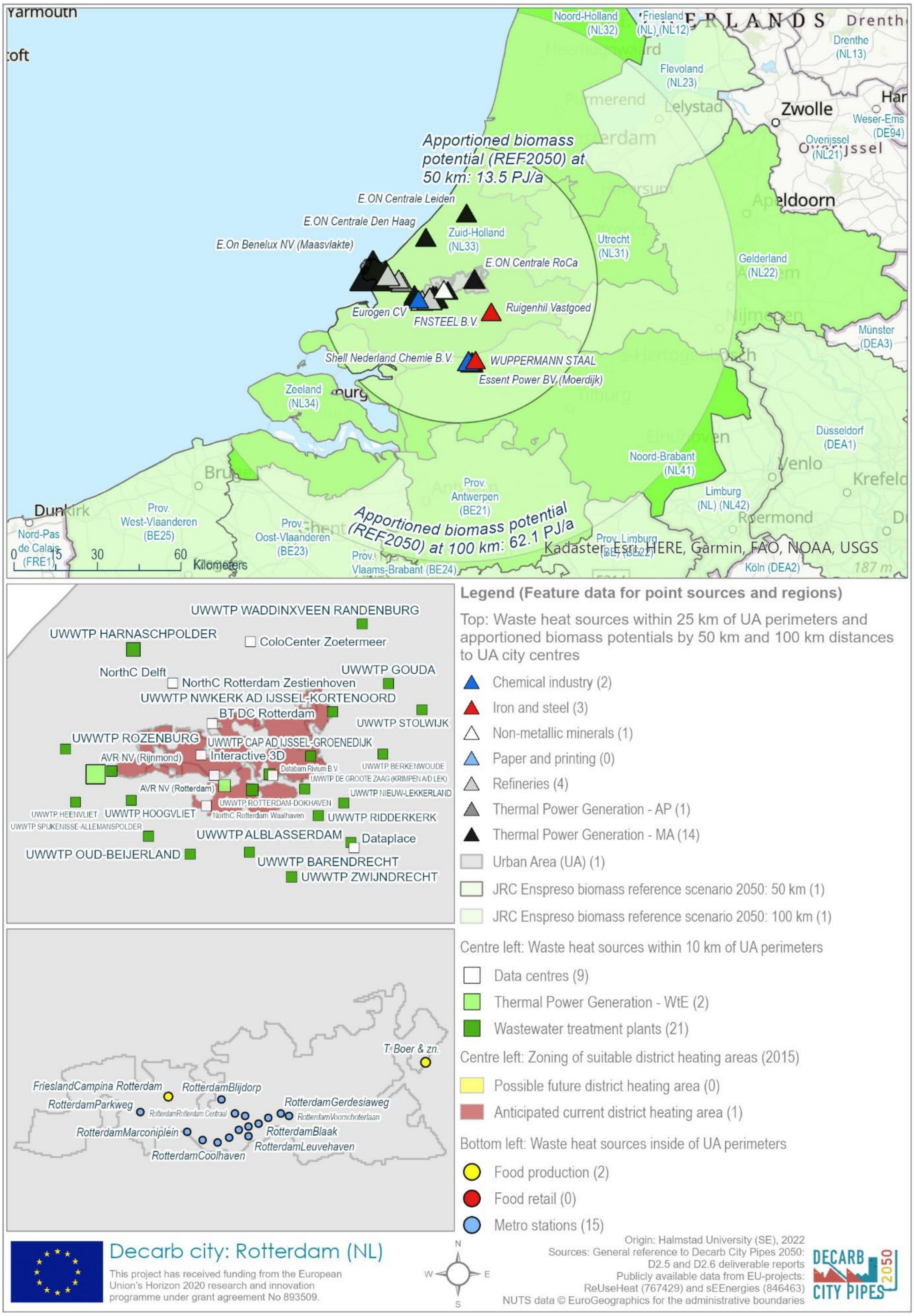


FIGURE 19. ROTTERDAM MAP OVERVIEW 2: 2050 BIOMASS POTENTIALS (JRC ENSPRESO REFERENCE SCENARIO) APPORTIONED BY 50 KM AND 100 KM DISTANCES TO CITY CENTRE, WASTE HEAT SOURCES INSIDE, WITHIN 10 KM, AND WITHIN 25 KM OF UA'S PERIMETER, AND ZONING OF SUITABLE DISTRICT HEATING AREAS UNDER CURRENT CONDITIONS. SOURCES: [27, 34, 39, 43].

Rotterdam's renewable and waste heat potential sources are illustrated in Figure 19 above. Although with the amounts of 13.5 PJ/a within 50 km and 62.1 PJ/a within 100 km distances, as shown in the top map, the apportioned biomass potential cannot be considered outstanding, in particular not since, as discussed under the Munich subsection above, this potential probably is even more imaginary in this case given the generally high concentration of human settlements in this part of Europe. However, as also stated above, the city takes advantage of numerous waste heat sources, more specifically, from chemical industries, iron and steel plants, refineries, as well as from a multitude of thermal power generation units located within 25 km of the city centre. As can be seen in the middle map of Figure 19, within a 10 km radius, the city should also have access to two operating waste-to-energy incineration power plants, several data centres, and no less than 21 wastewater treatment plants within 10 kilometres from the perimeters of the city urban area. Inside the urban area boundaries, additionally, there are also unconventional low-grade waste heat sources such as food production units and metro stations.

From the above presentation, we would expect distribution capital cost curves clearly above the study average (for this purpose, by the way, please see result section Figure 27, which presents study average cost curves for both the BL2050 and the FE2050 scenario settings), but still fairly permitting of city-wide investments and considerable heat market shares for district heating. Figure 20, at left (BL2050 scenario), does indeed confirm these expectations, as does annex Figure 37 (at left) with respect to the FE2050 scenario setting, with a distinct high market-entry cost in the order of five euro/GJ, and from there, close to 40% of the city heat market within reach at marginal capital costs below 10 euro/GJ. Correspondingly, in the frozen efficiency 2050 scenario, not very much district heat is likely to ever be distributed in Rotterdam at marginal cost levels below five euro/GJ (<10% of the heat market), but under this setting, approximately 55% of the urban area total heat market should be within reach at marginal costs not exceeding 10 euro/GJ.

As for the distribution of the city's heat demand by heat demand density classes, a principal status quo seems to be the case in the FE2050 scenario (see annex Figure 37 at right), whereas the radar diagram for the baseline 2050 scenario (Figure 20, at right) indicates only marginal changes compared to the base year: the share of heat demand density within 120 to 300 TJ/km^2 interval will slightly decline, mostly in favour of the 20-50 TJ/km^2 class.

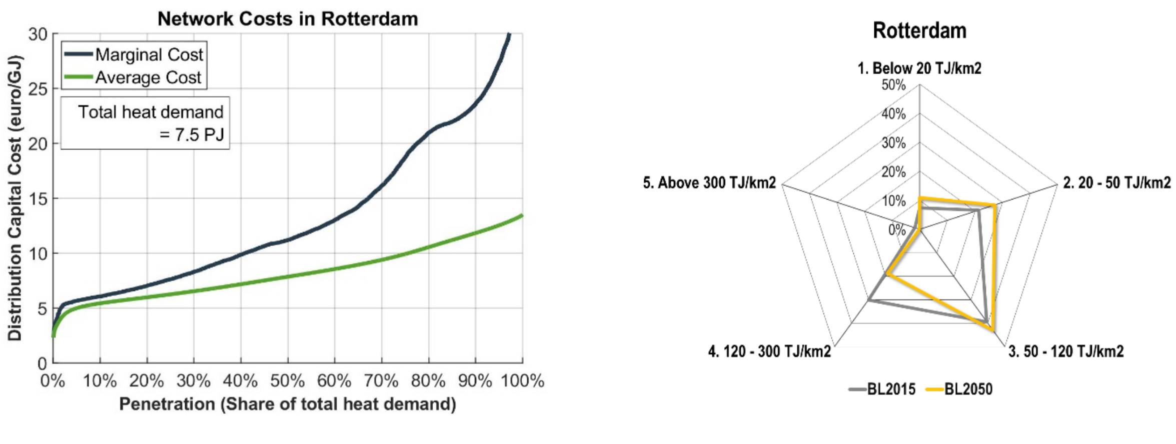


FIGURE 20 MARGINAL AND AVERAGE DISTRIBUTION CAPITAL COST LEVELS AND THE CORRESPONDING DISTRICT HEAT MARKET SHARES IN ROTTERDAM FOR BL2050 [€/GJ] (LEFT). COST LEVELS REFLECT COSTS FOR BOTH DISTRIBUTION AND SERVICE PIPES. AT RIGHT, RADAR DIAGRAM WITH RELATIVE SHARES INDICATING THE DISTRIBUTION OF TOTAL CITY HEAT DEMAND BY FIVE HEAT DEMAND DENSITY CLASSES (CURRENT YEAR INCLUDED FOR REFERENCE (BL2015)).

3.2.6. Vienna

The Austrian capital, Vienna, is the largest city in the country, with approximately two and a half million inhabitants in the larger metropolitan area, as well as the largest city in the DCP2050 project. From the heat demand density maps of the urban area of Vienna, as shown in Figure 21 on top for the BL2050 scenario and in annex Figure 40 for the FE2050 scenario, we recognise again, as in the case of Munich, the typical outline of a very large city, which over time has developed from a dedicated, and very dense, city centre (heat demand densities at or above 3000 GJ/ha), outwards into successively less dense outer city areas and suburbia.

The performance of Vienna regarding each structuring criterion alongside the cities' average is reported in Table 11. The city enjoys abundant renewable capacity compared to the other cities bearing in mind that its potential is more than twice the average (bearing in mind also the above subsection 3.2.4 discussion on the complexity of biomass as a readily available resource for heating and cooling purposes). Still, at a total of some 174 PJ annually (~48 TWh) within the 100-kilometre distance, and at some 39 PJ (~11 TWh) at the 50-kilometre limit, as also illustrated graphically in the top map of Figure 23 (Vienna map overview 2), biomass should likely represent a potent alternative in any Viennese decarbonisation strategy. Noteworthy, certain shares of these biomass resources could also be found, or converted, into gaseous form, for example biomethane from wastewater treatment sludge.

In addition, if further restricting the considered biomass potential data (Enspreso reference scenario, see Table 1 above for further references) to only consist of forestry, agricultural, and waste sector residues (hence excluding all primary round wood as well as all bio commodities with a likely direct offset in transport sector applications (oil crops for biodiesel, sugar beet for bioethanol, starchy crops etc.))[19], the surroundings of Vienna should still be rich in such renewable assets, as further presented in result section Table 18 below under the label “Biomass – PRIO”.

TABLE 11. VIENNA CITY DATA FOR THE TEN STRUCTURING CRITERIA AND ASSOCIATED AVERAGE VALUES FOR THE SEVEN DCP2050 CITIES

Structuring criteria	Vienna	DCP2050 average
City population	25%	-6%
Heating index	99	97
Heat Demand Density	45%	37%
Individual energy efficiency	3.0	3.8
Structural energy efficiency	80%	57%
Dependency on fossil fuels	46%	64%
Potential for renewable sources	173.7	80.5
Potential for waste heat	14.1	13.7
Development of the built environment	35%	21%
Coverage of district heating	39%	25%

The city is found to have a relatively low dependency on fossil fuels (compared to average), however, notably, 42% of the stated 46% constitutes natural gas mainly for individual use.

[19] Earlier this year, such a ”further restriction” was performed as a special task in the ENER C1 2019-482 tender project [65]. The various data on biomass potentials elaborated here represent city-specific extracts from this task.

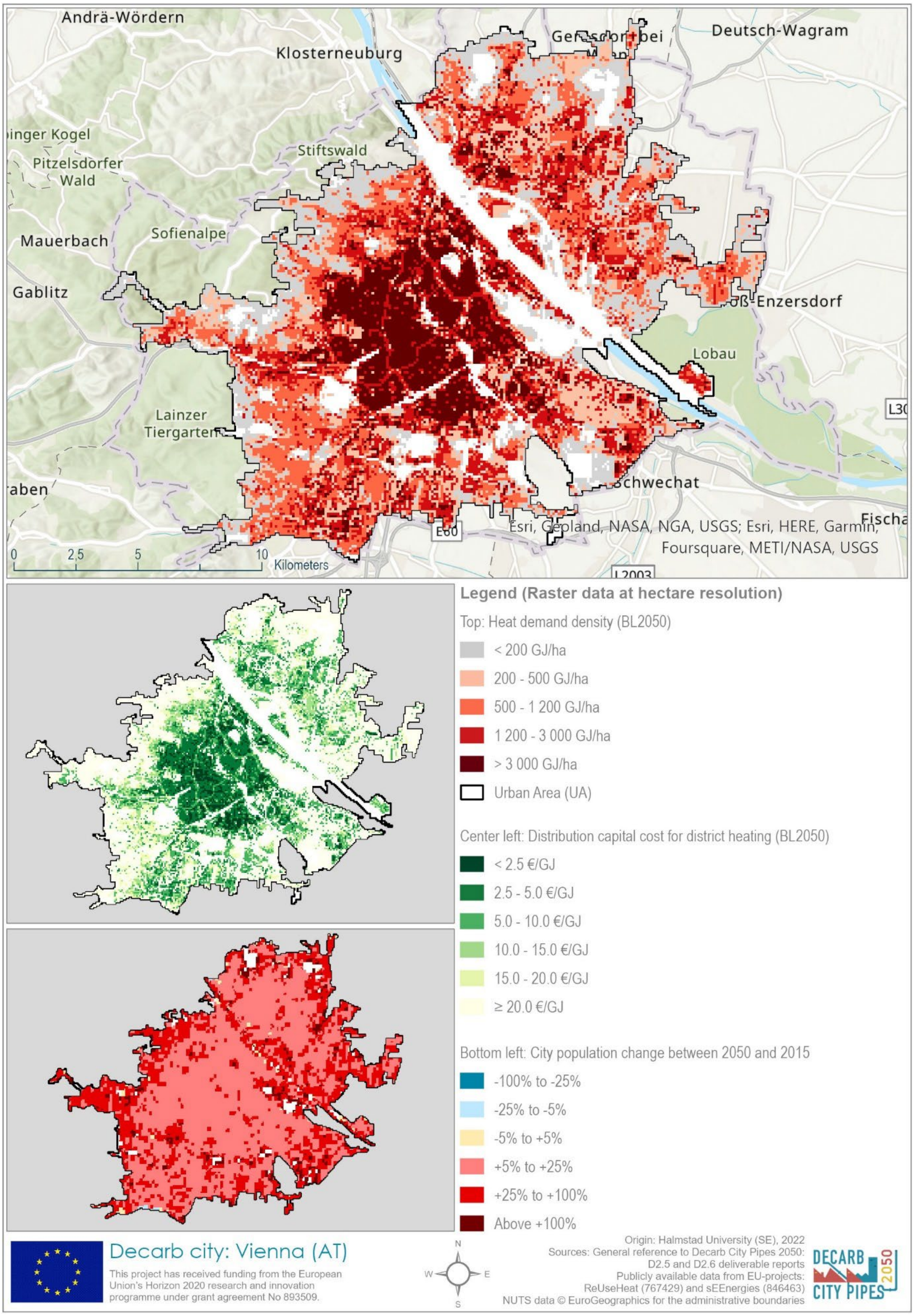
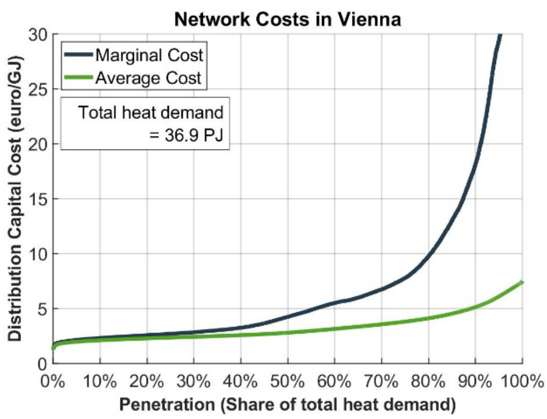


FIGURE 21. VIENNA MAP OVERVIEW 1: HEAT DEMAND DENSITY IN 2050 (BASELINE), DISTRIBUTION CAPITAL COST FOR DISTRICT HEATING IN 2050 (BASELINE), AND RELATIVE CHANGE IN CITY POPULATION BETWEEN 2050 AND 2015. SOURCES: [27, 44, 46, 50].

Although not explicitly stated in the used input data, it is like that the city´s current district heating system uses additional supplies of natural gas in central heat production, so the actual dependency on fossil fuels in the city remains somewhat uncertain. However, the current district heating system covers 39% of the total heat demand, which is above the study average as well as indicative of the fact that the city since long is exploiting the benefits of high inner-city heat demand densities by means of structural energy efficient measures. According to the high score (80%) in this criteria metric, i.e. structural energy efficiency, it may further be concluded that these beneficial opportunities will continue to be present also in the future city. However, the city's growing population, which could be synonymous with higher total volumes of future demand, should be taken into account when arranging decarbonisation plans. Besides, the city's index regarding the development of the built environment is slightly higher than the average, thus needing further consideration.

As for the other project cities, the BL2050 heat demand density map, the corresponding distribution capital cost map, and the expected population change by 2050, in Vienna, are presented in Figure 21 (see annex Figure 40 for the corresponding FE2050 images). As can be seen on top in Figure 21, many areas within and around the city centre have a high heat demand density of 3000 GJ/ha or above (~830 TWh). Distribution capital costs for district heating for the majority of these areas are below 5 euro/GJ, (representing in fact an upper threshold cost level for more than 50% of the total heat market, as indicated by the marginal cost curve in Figure 22 at left). The bottom map in Figure 21 shows that the city's population would be more or less evenly increasing by 2050, where this growth would be 5%-25% in most of the areas.

Figure 22 presents the distribution capital cost curve of the city for different district heating market shares under the BL2050 setting (see appendix Figure 39 for the FE2050 ditto). Together with Bilbao, Vienna displays by far the best suitability for feasible heat distribution, as indicated by the comparably low and continuously flat cost curves. Even under the ambitious baseline scenario, 80% of the heat market could be reached at marginal costs below 10 euro/GJ. The radar chart in the figure shows that the city's heat demand density in 2050 would be almost uniformly distributed among the classes under this scenario.



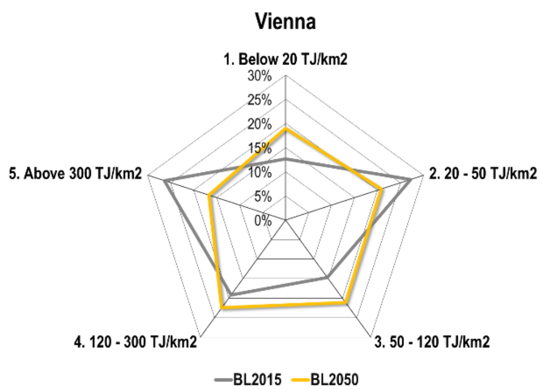


FIGURE 22. MARGINAL AND AVERAGE DISTRIBUTION CAPITAL COST LEVELS AND THE CORRESPONDING DISTRICT HEAT MARKET SHARES IN VIENNA FOR BL2050 [€/GJ] (LEFT). COST LEVELS REFLECT COSTS FOR BOTH DISTRIBUTION AND SERVICE PIPES. AT RIGHT, RADAR DIAGRAM WITH RELATIVE SHARES INDICATING THE DISTRIBUTION OF TOTAL CITY HEAT DEMAND BY FIVE HEAT DEMAND DENSITY CLASSES (CURRENT YEAR INCLUDED FOR REFERENCE (BL2015)).

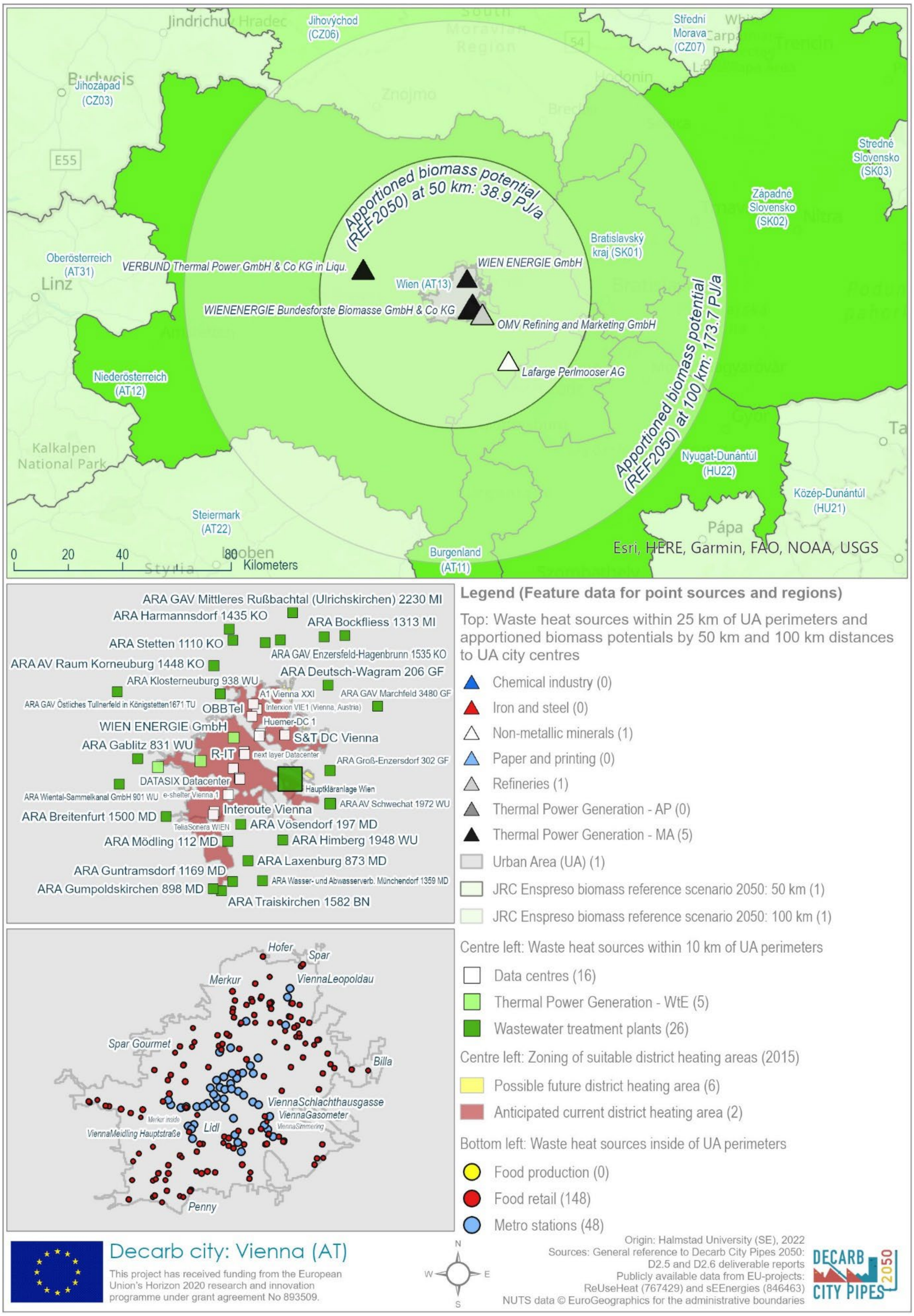


FIGURE 23. VIENNA MAP OVERVIEW 2: 2050 BIOMASS POTENTIALS (JRC ENSPRESO REFERENCE SCENARIO) APPORTIONED BY 50 KM AND 100 KM DISTANCES TO CITY CENTRE, WASTE HEAT SOURCES INSIDE, WITHIN 10 KM, AND WITHIN 25 KM OF UA'S PERIMETER, AND ZONING OF SUITABLE DISTRICT HEATING AREAS UNDER CURRENT CONDITIONS. SOURCES: [27, 34, 39, 43].

Vienna's potential for renewable energy, mentioned in the beginning of this subsection, and its waste heat potentials are illustrated in Figure 23 (Vienna map overview 2). As already stated, the city's apportioned biomass potential within the 100 km distance setting is in excess of 170 PJ/a, which the highest among project cities. Besides, there are five large-scale thermal power generation facilities, one refinery, and one non-metallic mineral unit in less than 25 km from the city centre that could be considered in heat recovery arrangements. Moreover, at the 10 km setting and within the urban area itself, there exist a multitude of other possible waste heat sources, such as waste-to-energy power plants (5), wastewater treatment units (26), data centres (16), metro stations (48), and an approximate 148 food retailers – all of which should be considered as alternative sources of heat supply when moving towards a greener H/C system in Vienna.

3.2.7. Winterthur

Winterthur, located in northern Switzerland near the German border, is the smallest and least populated city out of the seven considered project cities. With nearly 110,000 residents, Winterthur is Switzerland's sixth largest city by population. The city's climate is characterized as warm and temperate, with significant rain precipitation throughout the year. The city intends to achieve zero carbon emissions and a 100% renewable energy supply in 2050 by pursuing various plans, such as phasing-out gas connections from buildings.

Unfortunately, as was mentioned in the introduction (see subsection 1.3), a consequence of the applied approach (a coherent methodological framework utilising comparable publicly available data) is that very little information was available for Winterthur among the used repositories. Regarding the ten structuring criteria under consideration, four scores could be determined from the predominantly EU-scoped input data, as presented in Table 12. As can be seen in the table, the city´s district heating systems cover one-fifth of the city's current demand and the potential of the city's renewable sources is 81 PJ/a (biomass potential at 100 kilometres setting), which very close to the other cities' average. The city's heating index is also near the average and with a 70% dependency of the city's heating and cooling systems on oil and gas (once again, as for Vienna, assumedly relating to decentral applications whereas the constituent district heating supply mix is not reported, see also footnote 13 above), the numbers are indicative of a quite carbon emission-intensive current energy supply.

TABLE 12. WINTERTHUR CITY DATA FOR THE TEN STRUCTURING CRITERIA AND ASSOCIATED AVERAGE VALUES FOR THE SEVEN DCP2050 CITIES

Structuring criteria	Winterthur	DCP2050 average
Heating index	104	97
Dependency on fossil fuels	70%	64%
Potential for renewable sources	81.2	80.5
Coverage of district heating	20%	25%

Due to the lack of applicable data for the city, in particular concerning future year data on heat demand densities upon which basis district heat distribution capital costs could have been calculated, map overviews 1 and 3 were not possible to establish. Since, however, Switzerland is represented in the used biomass potential data, a Winterthur map overview 2 was, at least partly, conceivable in this context (see Figure 24 on top for the visual illustration of apportioned biomass potentials at 50 km and 100 km distance settings).

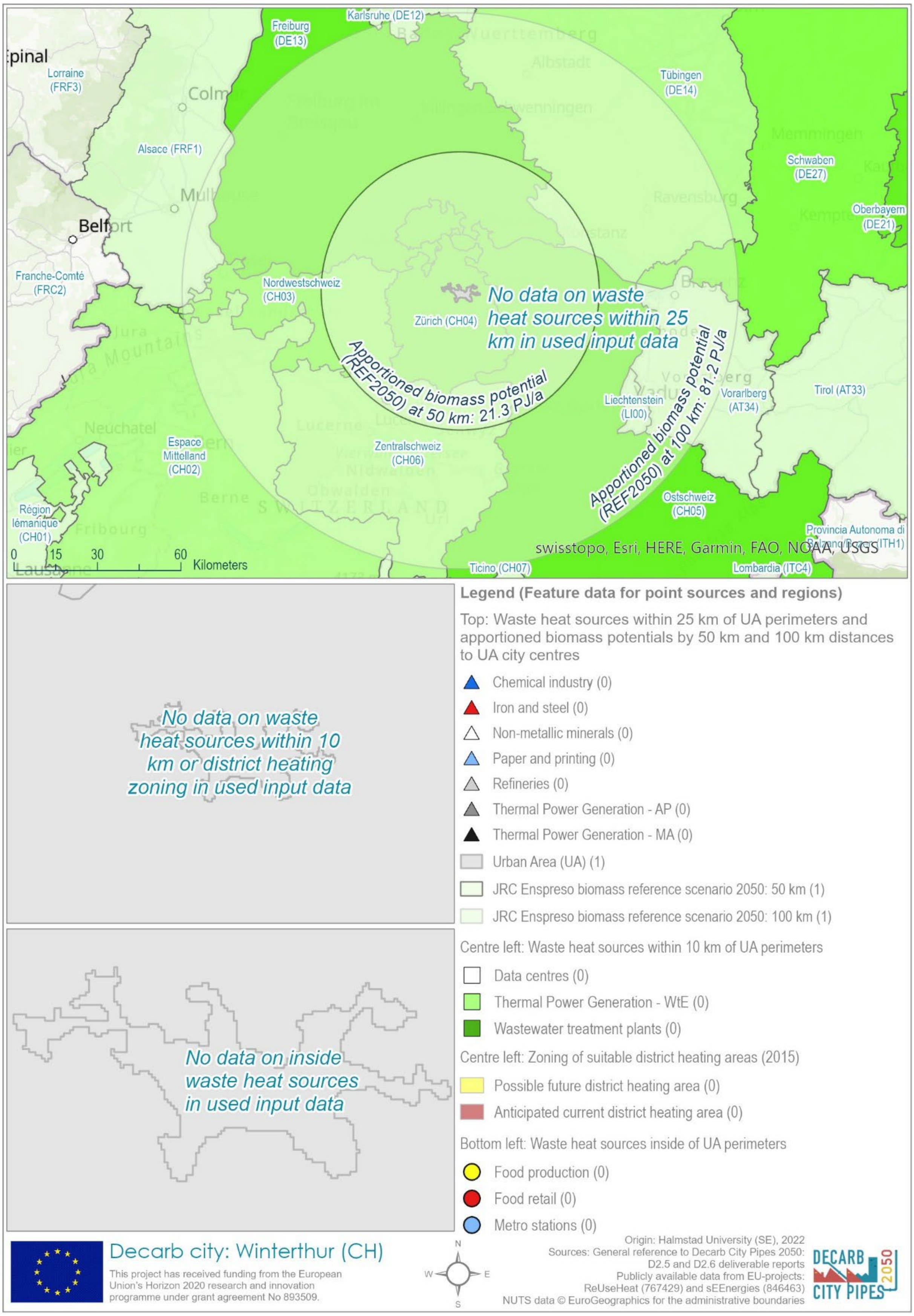


FIGURE 24. WINTERTHUR MAP OVERVIEW 2: 2050 BIOMASS POTENTIALS (JRC ENSPRESO REFERENCE SCENARIO) APPORTIONED BY 50 KM AND 100 KM DISTANCES TO CITY CENTRE, WASTE HEAT SOURCES INSIDE, WITHIN 10 KM, AND WITHIN 25 KM OF UA'S PERIMETER, AND ZONING OF SUITABLE DISTRICT HEATING AREAS UNDER CURRENT CONDITIONS. SOURCES: [27, 34, 39, 43].

To still provide some orientation as for the heat demand distribution in the city of Winterthur, Figure 25, at left, reproduces a current year (2019) heat demand density map of the city, which was part of a previous DCP2050 deliverable report (D2.2, see further footnote 2 above) and rendered by interpretation of domestic data from the Swiss Federal Office of Energy [66]. As can be seen, there are some zones in the centre of the city where heat demand densities are distinctly high, over 3000 GJ/ha according to the input data. This very-high density inner-city region is surrounded by areas that hold moderate to high heat demand densities above 500 GJ/ha, or in some places over 1200 GJ/ha. These statistics denote that the city, generally speaking, is dense enough in terms of heat demand to make it an economically apt case for using, and most likely, expanding district heating.

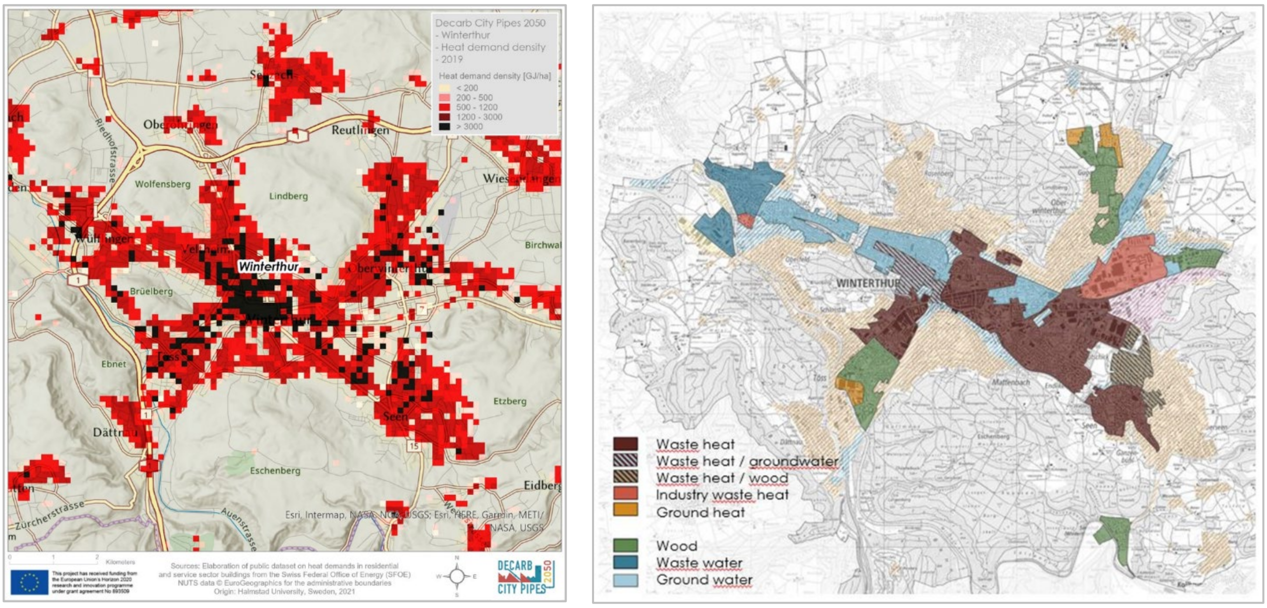


FIGURE 25. LEFT: MAP OF HEAT DEMAND DENSITY BY HECTARES IN THE CITY OF WINTERTHUR, AS ASSESSED FOR CURRENT CONDITIONS BASED ON DATA FROM THE SWISS FEDERAL OFFICE OF ENERGY. SOURCE: [66]. RIGHT: CITY MAP WITH ANTICIPATED HEAT SOURCES FOR DISTRICT HEATING IN WINTERTHUR BY 2035, AS ASSESSED BY THE CITY OF WINTERTHUR.

For further reference and orientation, the right map in Figure 25 reproduces an in-house heat resource map developed by the Winterthur city administration as part of the LWG´s work on H/C outlooks and heat planning (see reference [42] for further information). Apart from depicting the anticipated heat sources in the city for the year 2030, the map itself bears witness of the high level of detail by which the city is approaching the challenge of formulating its decarbonisation strategy. Waste heat is the most highlighted source accessible in the centre and eastern neighbourhoods of the city. Groundwater is also a sizeable source, mostly in northwest areas. There are also scattered districts where wood could be considered an energy source.

4. Discussion on framework approach

The key motivation behind the development of a coherent methodological framework was to facilitate the simultaneous address of several multiple objectives associated with the final tasks of Work package 2 in the DCP2050 project. As has been described detailed in the above referenced WP2 reports, these multiple objectives required, as a starting point, a common mechanism whereby to characterise urban areas by a set of easily comprehensible typologies, and, in turn, whereby to associate a corresponding set of characteristic decarbonisation design approaches on the basis of these typologies. In the D2.5 report, this initial part of the framework was referred to as a “database-driven urban typology”, and it represents the main contents of the framework to be discussed. Noteworthy, a key point is that the choice of structuring criteria is dependent on data availability (ideally publicly available data for all seven project cities). Without this dependency, other structuring criteria parameters could be considered.

4.1. Design approaches based on urban typologies

The six decarbonisation design approaches chiselled out within the framework are crafted as suggestive action-packages characteristic for distinct urban typologies that are thought derivable based on access to underlying input data (a database-driven urban typology). The typologies are intended to work independently of the spatial resolution and may thus refer to cities as such, to city districts, to neighbourhoods, or to any settlement area of interest. However, a distinction should be made whether the application objective is a cross-city synthesis or an in-depth sub-city level analysis, since the typology definition by classification based on ratings for five structuring criteria is more appropriate for the former, and less so for the latter.

To provide guidance and instructions for the latter case, that is when the application objective is an in-depth sub-city level analysis, the three framework typologies are presented in the following with focus on the structuring criteria of heat demand density as the key distinguishing parameter[20]. Hereby, the three urban typologies and the respective short-term and long-term decarbonisation design approaches, may be expressed and listed as:

- *Urban H/C Type 1*
    - This typology is characterised by high heat demand density and refers therefore mainly to central supply solutions.
    - Short-term design approach (Type 1):
        - Consider to expand current district heating into new areas and, where applicable, plan for conversion to low-temperature operation. Increase

[20] Selecting heat demand density as key distinguishing parameter is recommendable for this purpose since it is directly reflective of the spatial distribution and magnitude of building heat demands. But, given limited availability of underlying data, other parameters such as population density could work as a proxy. Depending on study objective, it is also conceivable to use other structuring criteria such as, for example, the potentials for renewable sources and waste heat in order to designate suitable decarbonisation design approaches to certain city districts. Similarly, for cooling provisions, georeferenced data on cold demand densities could be used to delineate certain high-demand areas suitable for district cooling system applications.

connection rates to these systems and, if there is no district heating at current, begin preparations for the installation of new systems.

    - Assess the potentials for energy from wastes and the integration of renewable and waste heat sources to replace current central fossil supply (deep and shallow geothermal energy, large-scale heat pumps, all kinds of waste heat, sustainable biomass, solar thermal, water bodies in vicinity etc.) and decide, where applicable, which areas that should be disconnected from gas and when.

  - Long-term design approach (Type 1):
    - Expand current district heating into new areas and, if no district heating exists today, plan and build new systems. Focus on maintained high heat density in the built environment in these areas and establish long-term urban planning strategies for both heat and cold supplies.
    - Seek to spatially coordinate the expansion and new construction of district heating systems with the orderly phase-out of fossil-based supplies, arrange for energy from wastes capacities and the systematic integration of renewable and waste heat sources in the central supply. Focus on central energy storage solutions.

- *Urban H/C Type 2*
  - This typology is characterised by average heat demand density and refers therefore to both central and individual supply solutions.
  - Short-term design approach (Type 2):
    - In districts with sufficiently high heat demand densities, consider to expand current or prepare for new district heating systems, increase connection rates, and plan for conversion to low-temperature systems where applicable (decentralised networks or networks connected to a centralised system). Consider energy zoning and, at lower densities, prioritise investments in individual energy efficiency measures.
    - Assess the potentials for energy from wastes and the integration of renewable and waste heat sources to replace current central and individual fossil supplies. Special focus on individual electrification of heat demands especially in less dense areas. Decisions on which areas should be disconnected from gas and when.
  - Long-term design approach (Type 2):
    - Introduce new, or expand current, district heating systems in districts with sufficiently high heat demand densities, establish as high connection rates as possible, and seek long-term densification of these areas. Apply energy zoning (perhaps under mandatory connection principles), and arrange support for building refurbishments, energy savings, and individual electrification of heat demands in less dense areas.
    - Convert to low-temperature district heating systems where applicable in order to facilitate higher direct integration of renewable and waste

heat sources to replace current central supply. Electrify individual heat demands to replace current individual fossil supply.

- *Urban H/C Type 3*
  - This typology is characterised by low heat demand density and refers therefore mainly to individual supply solutions.
  - Short-term design approach (Type 3):
    - Investigate possibilities and suitable support for energy savings in the current building stock, initiate refurbishment activities, and replace old fossil-based heat supply systems with focus on individual building or building block installations.
    - Seek electrification of heat demands by use of individual heat pumps, perhaps by utilisation of shallow geothermal energy resources, ground water assets, roof-mounted solar photovoltaic panels, air, and similar.
  - Long-term design approach (Type 3):
    - Perform energy savings in the current building stock by the orderly arrangement and enforcement of refurbishments activities, focus on programs for high-efficiency future buildings (passive houses, etc.), and, in districts in close vicinity to low-temperature district heating systems, plan for possible future connections.
    - Maintain focus on the electrification of building heat demands by use of individual heat pumps with support also for other individual solutions, such as geothermal probes as building-level storage systems combined with solar thermal panels, utilisation of local green gases based on residues from regional forestry and agriculture (perhaps by using existing infrastructures), as well as other locally available energy assets. Focus on individual energy storage solutions.

By this arrangement, using heat demand density as the key distinguishing parameter, the framework typologies are not only presented in a form more suitable for in-depth sub-city level analyses, they may hereby also be interpreted as representative of “physical suitability” for district heating, a concept previously introduced in [9].

4.2. Example of application at city district level (Dublin)

In this subsection, and as illustrated in Figure 26, the three typologies, thus established on the basis of heat demand density data at the hectare level (in this case according to a Frozen Efficiency scenario for 2050 (FE2050) since it is most representative of current conditions (see [46, 49, 67] for further references on used sEEnergies project scenarios and datasets)), are outlined as an example of application at the city district level for the city of Dublin.

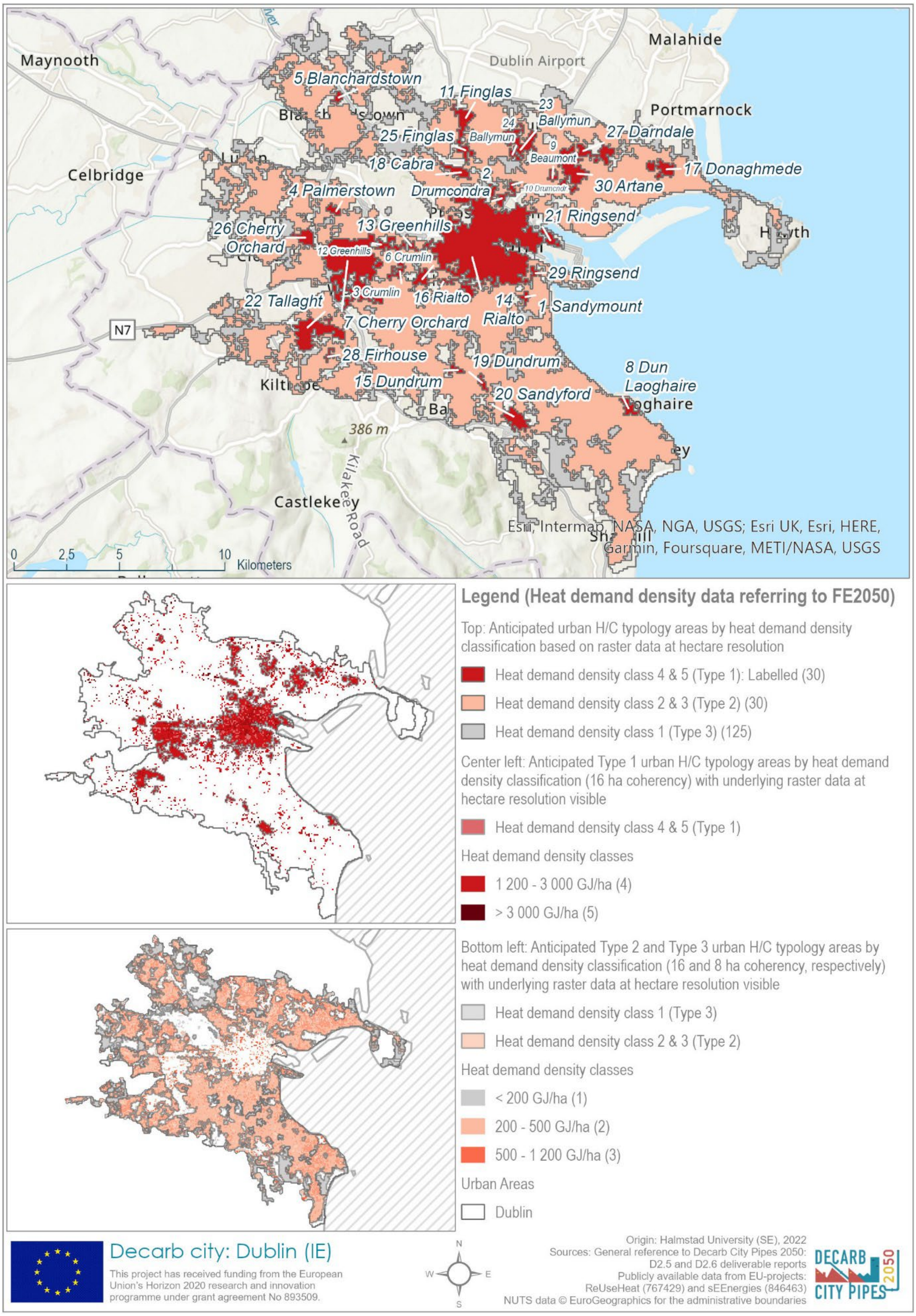


Figure 26. Dublin map overview 4: Anticipated urban H/C typology areas by heat demand density classification based on raster data at hectare resolution. Heat demand density data referring to Frozen Efficiency 2050 scenario (FE2050) as further explicated in the D2.6 report. Sources: [27, 46, 68].

The classification of heat demand density levels follows in this example well-established practise, as first suggested and introduced in [10] and subsequently elaborated among other in [49, 69], and is here adapted so as to represent the three urban typologies, where heat demand densities in class 5 (> 3000 GJ/ha) and class 4 (1200 – 3000 GJ/ha) are associated with Urban H/C Type 1; class 3 (500 – 1200 GJ/ha) and class 2 (200 – 500 GJ/ha) are associated with Urban H/C Type 2; and where class 1 (< 200 GJ/ha) is associated with Urban H/C Type 3.

The derivation of distinct typology areas, in the form of polygons, was performed in this case by a GIS (Geographical Information System) model sequence consisting of the following steps:

- *Extract by Attributes*
    - Extraction of three separate raster layers, one for each Urban H/C Type, from the FE2050 heat demand density raster dataset. For each of these layers, the following steps were performed:
- *Raster to Polygon*
    - Conversion to multipart feature data
- *Dissolve Boundaries*
    - Merge of adjacent feature parts into larger polygons
- *Eliminate Polygon Part*
    - Thresholds defined for eligibility to form larger coherent polygons (16 hectares for Urban H/C Type 1 and 2, eight hectares for Urban H/C Type 3)
- *Multipart to Singlepart*
    - Larger coherent polygons created as singlepart features by separating multipart feature data (generating unique ID´s for each polygon)
- *Spatial Join*
    - A one-to-one join based on closest geodesic distance from polygon borders to a point-source city-names dataset [68] to associate names to each polygon.

As can be seen in Figure 26, all three typologies are present within the overall urban area of Dublin, with, notably, 30 instances of Urban H/C Type 1 areas, a coincidental 30 instances of Urban H/C Type 2 areas as well, and an anticipated total of 125 Urban H/C Type 3 areas. By this distinction, the Irish capital would consist of no less than 185 delineated areas, or city districts, for which particular decarbonisation design approaches, according to the above, could be considered. In addition, some of the identified areas may be indicative of appropriate energy zoning, should that become part of the cities transition roadmap for 2050.

Noteworthy, also, from this example, and as presented in Table 13, is the fact that while the 30 Urban H/C Type 1 areas represent only 16% of the total count of areas, and only 18% of the charted city land area, this typology represents more than half of the total city heat demand (56%, or some 10,443 terajoules per year). Similarly, while by far representing the largest count (125 areas and 68% of the total count) and approximate one fourth of the land area, the Urban H/C Type 3 segment represents only four percent of the total heat demand (anticipated at 725 terajoules annually, or 0.7 petajoules per year, as indicated in the far-right column of Table 13).

These proportions, which are indicative of general conditions and not particularly unique for Dublin, may serve as a principal guideline and recommendation as for what typology segments to prioritise. It is clear that the reward for investments in energy efficiency measures, thus in terms of the total share of a city heat demand that will have been decarbonised, may be expected to be considerably larger in high and medium heat density areas compared to straight-out low-density areas.

TABLE 13. OVERVIEW SUMMARY OF URBAN TYPOLOGY DATA FOR THE CITY OF DUBLIN, WITH TOTAL VOLUMES AND RELATIVE SHARES BY COUNT, LAND AREAS, AND HEAT DEMANDS, UNDER A FROZEN EFFICIENCY 2050 SCENARIO

Dublin (IE)	Count [n]	Count [%]	Land area [ha]	Land area [%]	Heat demand [PJ]	Heat demand [%]
Urban H/C Type 1	30	16%	4930	18%	10.4	56%
Urban H/C Type 2	30	16%	15726	58%	7.6	41%
Urban H/C Type 3	125	68%	6245	23%	0.7	4%
Total	**185**	**100%**	**26901**	**100%**	**18.8**	**100%**

Regarding the middle segment, that is the group of Urban H/C Type 2 areas, Table 13 reveals the likewise important observation that, in the city of Dublin, these areas are generally much larger than the Urban H/C Type 1 areas, which is also quite visible in the centre and bottom maps in Figure 26. As a hands-on assessment, Urban H/C Type 2 areas extend to some 524 hectares on average (equivalent to 5.24 square kilometres), while the denser Urban H/C Type 1 areas cover some 164 hectares on average (or 1.64 square kilometres) under the given study assumptions and constraints.

For the Urban H/C Type 3 segment, as also observable in Table 13, the corresponding land area-average per typology area is found at only 50 hectares (0.5 square kilometres), which might be expected here because of the single representation by heat demand density class 1 only (< 200 GJ/ha). By the above referenced classification of heat demand density levels according to well-established practise, heat demand densities below 200 gigajoules per hectare are in fact often used to indicate non-urban, or rural, conditions. In the case of Dublin, the initial spatial analysis indicated relatively rich presence of such low-density areas within the urban area of the city, why the division by single representation was made.

In view of this effect, however, it is worth mentioning in general that the division by use of heat demand density classes becomes delicate as the perspectives move from highly dense inner-city areas towards less dense, and eventually, towards outright sparse areas at the perimeters of the urban area itself. As a remedy, the cross-section between Urban H/C Type 2 and Urban H/C Type 3 should be interpreted rather freely under consideration of the physical landscape and the unique local conditions of a studied city. If more suitable, the Urban H/C Type 3 segment could alternatively be defined so as to consist of both heat demand density classes 1 and 2, which then would render Urban H/C Type 2 areas only consisting of heat demand density class 3 as a consequence. Alternatively, the analysis could be rendered stand-alone for each heat demand density class separately, thus dissolving the typology concept somewhat. By flexible interpretation, nonetheless, the association of related decarbonisation design approaches should pose no real obstacles to such interpretations.

5. Cross-city synthesis

The results accounted for in this section refer on the hand to a city comparison (subsection 5.1) and, on the other, to a city ranking (subsection 5.2), which together constitute the main outputs for the sought cross-city synthesis. In both cases, the assembled input data for the ten structuring criteria, as described and defined in subsection 2.2.1 above, and as detailed for each of the project cities in main section 3 above, form the basis upon which these results have been established. Importantly, first of all, the main purpose of this account is to learn something about the differences in unique local conditions among the participating cities, hence, not to grade the cities or to suggest competition between them.

Secondly, as for example noted above concerning the level of detail and accuracy in reported shares of fossil fuels used in the cities (see e.g. footnote 13), any bias or outright lack of correctness in the used input data will have had influence on these results accordingly. We therefore want to stress that these results should be regarded as indicative estimates and not in any sense as verified and final statements. Once again, the main purport here is to introduce and test a coherent methodological framework approach which, among other, involves multi-criteria decision modelling and the use of directly comparable and publicly available input data. As for any scientific investigation, high level of detail and accuracy in used input data will generally facilitate high level of detail and accuracy in study results as well.

Additional disclaimers and aspects to bear in mind concerning the following findings are, thirdly, that for the criteria metric referring to renewable energy sources, if it should have included not only biomass, as in this case, but also deep geothermal, solar thermal, as well as other locally available potentials normally sorted under this category, the results would have likely been different. From the ongoing work in the LWG´s, it is already clear that deep geothermal, for example, is a main alternative considered in some of the project cities (Munich, in particular).

Fourthly, as briefly commented in footnote 16 above, anticipated future population developments are based on a combination of past trends, future forecasts, and quite sophisticated modelling assumptions, which should be remembered when viewing these results. The expected population developments, in this context particularly their anticipated spatial distribution and not merely their total numbers, are thus not to be apprehended as carved in stone, but rather recognised as qualified guesses.

Finally, for the modelling of district heating distribution capital costs and the corresponding assessments of heat market share penetrations at given cost levels, these calculations presuppose 100% connection rates to the district heating system, that is, calculated capital costs are representative of cost levels and market shares under a general assumption that all of the heat demand under consideration is capable of being met by district heat distribution, which perhaps seldom would be the real case. This circumstance is of minor significance as for the city comparison, but should be kept in mind when evaluating suggested cost and market share levels. Regarding considered waste heat sources, additionally, these refer to current year conditions (not to 2050) and excludes possible heat recoveries from nuclear facilities. It is not unlikely that the European industrial landscape will look quite different thirty years from now in terms of waste heat opportunities, with a fundamental transition to electrification and hydrogen-based processes already happening.

5.1. City comparison

For the city comparison, a closer look on the expected absolute and relative population changes between 2050 and 2015 may be an appropriate starting point, as outlined in Table 14. The absolute numbers in the left columns of this table, indicate by million inhabitants the anticipated future population within the Urban Area (UA) perimeters of each city, and, in the right columns, the relative change in these population counts between the years 2015, 2030, and 2050. The total sum population of the project cities (excluding Winterthur) is anticipated to be very close to six million in 2050 (5.65 million at current), representing a 6% increase relative to the base year. This increase is primarily due to the developments in Vienna and Munich, as the two cities have the highest populations in absolute numbers while, simultaneously, being expected to experience the largest relative increases of inhabitants as well. In fact, total resident counts in all other project cities are expected to decrease (once again, excluding Winterthur), ranging from less than 3% in Dublin to around 34% in Bilbao.

TABLE 14. ABSOLUTE AND RELATIVE CHANGE IN TOTAL POPULATION INSIDE URBAN AREAS PERIMETERS BETWEEN 2050 AND 2015

	City population [Mn]			Relative change from 2015 [%]		
Name	**POP_2050**	**POP_2030**	**POP_2015**	**POP_2050**	**POP_2030**	**POP_2015**
Bilbao	0.490	0.638	0.742	-34.0%	-14.1%	0.0%
Bratislava	0.228	0.298	0.339	-32.5%	-11.9%	0.0%
Dublin	1.072	1.090	1.098	-2.4%	-0.8%	0.0%
Munich	1.745	1.580	1.374	27.0%	15.0%	0.0%
Rotterdam	0.329	0.376	0.394	-16.6%	-4.6%	0.0%
Vienna	2.120	1.948	1.698	24.8%	14.7%	0.0%
Winterthur	-	-	-	-	-	-
Grand total	**5.984**	**5.930**	**5.646**	**6.0%**	**5.0%**	**0.0%**

Although the population development, by itself, is an important indicator among the ten structuring criteria, in particular concerning the projection of future heat demand in buildings, it is essential for this purpose to also consider its projection simultaneously with that of future floor areas (Table 15) and subsequently with that of heat demand density (Table 16). Table 15 shows the anticipated floor areas of the cities in 2015 and 2050 alongside the relative change over these years.

TABLE 15. RELATIVE CHANGE IN TOTAL FLOOR AREAS INSIDE URBAN AREAS PERIMETERS BETWEEN 2050 AND 2015

	Floor areas (Urban Areas)		
Name	**Change [%]**	**2050 [Mm2]**	**2015 [Mm2]**
Bilbao	16.4%	38.3	32.9
Bratislava	17.9%	26.2	22.2
Dublin	29.0%	71.1	55.1
Munich	6.5%	71.6	67.3
Rotterdam	23.5%	36.0	29.2
Vienna	34.6%	111.6	82.9
Winterthur	-	-	-
Grand total	**22.6%**	**354.9**	**289.6**

As can be seen in Table 15, all the cities are expanding in terms of million square meters of residential and service sector floor areas within each respective city urban area (by a noteworthy total increase of ~23%). Vienna is the city with the largest floor area, and is also supposed to have the highest growth rate. Although placed in the second position regarding total floor areas, Munich has the lowest expansion rate, with a 6.5% increase by 2050.

Regarding the cities' heat demand densities, Table 16 presents, by reference to two thresholds relating to heat demand density classes (50 TJ/km^2 and 120 TJ/km^2 respectively[21]), for the current year (BL2015), the baseline 2050 scenario (BL2050), and for the frozen efficiency scenario (FE2050), those percentage shares of total city heat demands that are found, on the one hand, below (left columns), and, on the other hand, above these thresholds (centre and right columns).

The motivation for this mode of presentation is that, depending on different views and evaluations of direct feasibility for network heat distribution, be it that of conventional so-called 3rd generation operation (often associated with direct feasibility above 120 TJ/km^2) or so-called low-temperature 4th generation operation (associated with feasibility above 50 TJ/km^2), the far right and centre tabular shares respectively should be indicative of feasible future district heating heat market shares, at least in terms of underlying "physical suitability" (i.e. heat demand density, see footnote 17 above for further references). Conversely, the far-left columns (relative shares below 50 TJ/km^2), may serve as an appreciation of heat market shares more suitable for individual heat supply technologies.

TABLE 16. PERCENTAGE SHARE OF TOTAL HEAT DEMAND IN URBAN AREAS (UA) AT GIVEN THRESHOLDS RELATING TO DIRECT FEASIBILITY OF DISTRICT HEAT DISTRIBUTION

	Percentage share below 50 TJ/km^2			Percentage share above 50 TJ/km^2			Percentage share above 120 TJ/km^2		
Name	**FE2050**	**BL2050**	**BL2015**	**FE2050**	**BL2050**	**BL2015**	**FE2050**	**BL2050**	**BL2015**
Bilbao	42%	47%	41%	58%	53%	59%	41%	38%	41%
Bratislava	33%	72%	31%	67%	28%	69%	41%	8%	43%
Dublin	63%	75%	63%	37%	25%	37%	18%	4%	22%
Munich	33%	34%	33%	67%	66%	67%	46%	34%	52%
Rotterdam	29%	38%	29%	71%	62%	71%	30%	19%	32%
Vienna	38%	40%	40%	62%	60%	60%	45%	39%	46%
Winterthur	-	-	-	-	-	-	-	-	-
Grand total	**40%**	**51%**	**39%**	**60%**	**49%**	**61%**	**37%**	**24%**	**39%**

A first noticeable observation from Table 16 is that the above-mentioned overall physical suitability for conventional (3rd generation) district heat distribution (averaging at 39% in the BL2015) is far higher for the current year than the reported city average on the "Coverage of district heating" criteria metric (found at 25% in the decision data matrix presented in Table 19 below). This would imply that structural energy efficiency measures have been historically deselected in favour of other, individual, measures, and that there should be room for expanding district heating already at current conditions. Comparing the FE2050 scenario with BL2015, moreover, there would not be a substantial change in the shares

[21] Corresponding magnitudes and units: 50 TJ/km^2, 13.9 GWh/km^2, 500 GJ/ha, 138.9 MWh/ha, and 120 TJ/km^2, 33.3 GWh/km^2, 1200 GJ/ha, 333.3 MWh/ha.

above 50 TJ/km² or above 120 TJ/km², meaning that, under this scenario, current possibilities are principally maintained.

However, when considering the BL2050 scenario versus the BL2015 reference, a decrease in the average share of urban areas with high heat demand density is recognisable. This reduction corresponds to minus ~38% at the above 120 TJ/km² threshold (24% compared to 39%), and minus ~20% at the above 50 TJ/km² setting (49% compared to 61%). To put these observations into further perspective, recalling the numbers on total city heat demands for the various scenario settings, as presented in Table 5 above, and relating to the BL2015 setting as the current year reference (total heat demand for the project cities at 141.9 PJ/a, or 39.4 TWh/a, excluding Winterthur), the FE2050 total (140.1 PJ/a, or 38.9 TWh/a) and the BL2050 total (97.5 PJ/a, or 27.1 TWh/a) represent reductions of -1.2% and -31.3% respectively. From this, it appears that, where total heat demands are decreasing, the relative decrease in high heat-demand density areas is larger than the total relative decrease, in other words quite the opposite of densification and itself an additional indication of urban sprawl tendencies among some of the project cities.

In consideration of each of the cities individually, the result is principally the same, albeit with some variations. Changes in total heat demands relative the BL2015 reference, as presented in Table 5, range from -6.6% (Munich) to plus 10.1% (Rotterdam) in the FE2050 projection, and from -8.5% (Bilbao) to no less than minus 66.5% (Bratislava) in the BL2050 scenario. In parallel, while all cities experience floor area increases, in the range from 6.5% (Munich) to 34.6% (Vienna), with an average at 22.6% (as outlined in Table 15), total city population changes are found in the range from minus 34.0% decreases (Bilbao) to plus 27.0% increases (Munich), as presented in Table 14. Noteworthy, while at the current BL2015 setting 39% of total heat demands are found below the 50 TJ/km² threshold, principally half of the expected future heat demand under the more ambitious BL2050 projection (51%), would fall under this threshold (see far left columns in Table 16).

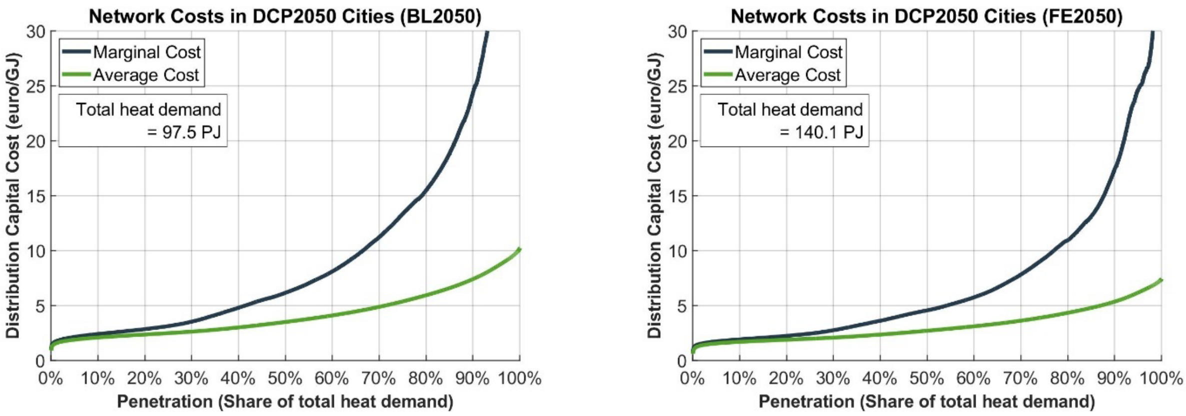


FIGURE 27. GRAND TOTAL MARGINAL AND AVERAGE DISTRIBUTION CAPITAL COST LEVELS AND THE CORRESPONDING DISTRICT HEAT MARKET SHARES IN SIX CITIES (EXCLUDING WINTERTHUR) FOR BL2050 (LEFT) AND FE2050 (RIGHT) [€/GJ]. COST LEVELS REFLECT COSTS FOR BOTH DISTRIBUTION AND SERVICE PIPES.

Despite these tendencies, which might be said not capable of causing cataclysmic changes in the current city landscapes, as expected, and as outlined in Figure 27 (at left for the BL2050 scenario and at right for the FE2050 scenario), the assessed marginal and average cost curves for network heat distribution display rather beneficial conditions for further investments and expansions of district heating in the project cities. Even under the more ambitious BL2050 scenario, 50% heat market shares – hence a doubling of the current average level for the project cities found at 25%, as detailed in the far right column of Table 19 – should be associated with marginal capital cost levels in the order of six to seven euro/GJ (20 euro/MWh – 25 euro/MWh), levels, which under the FE2050 scenario, are found at approximately five euro/GJ (18 euro/MWh).

These results, which are in general accordance with the shares of different heat demand density classes under the different scenarios, as reported in Table 16, are further explicated in Table 17. In this table, the found heat market penetration shares possible to attain at corresponding network cost levels are presented in an alternative format utilising six marginal cost classes, by which summaries are given for the total count of hectare grid cells, total land areas, total and accumulated relative shares of the heat demand, as well as for anticipated total investment volumes.

TABLE 17. SUMMARY OVERVIEW FOR MARGINAL DISTRIBUTION CAPITAL COSTS BY SIX COST CLASSES FOR THE PROJECT CITIES (EXCLUDING WINTERTHUR) UNDER THE BL2050 AND THE FE2050 SCENARIOS

	Hectares [n]		Land area [km²]		Heat demand [PJ/a]		Investment [M€]		Heat demand (Acc.) [%]	
Cost classes Marg. [€/GJ]	BL2050	FE2050	BL2050	FE2050	BL2050	FE2050	BL2050	FE2050	BL2050	FE2050
1. < 2.5	1838	5211	18.4	52.1	11.8	36.7	496	1432	12%	26%
2. 2.5 - 5.0	7216	10918	72.2	109.2	28.6	39.3	1931	2819	41%	54%
3. 5.0 - 10.0	13642	17735	136.4	177.4	24.5	32.0	3383	4401	67%	77%
4. 10.0 - 15.0	13992	18203	139.9	182.0	12.3	15.0	2986	3540	79%	88%
5. 15.0 - 20.0	10759	9345	107.6	93.5	7.0	6.0	2365	2030	86%	92%
6. > 20.0	52331	38366	523.3	383.7	13.4	11.2	8321	6094	100%	100%
Grand Total	**99778**	**99778**	**997.8**	**997.8**	**97.5**	**140.1**	**19482**	**20316**	**-**	-

From Table 17 it can be concluded that a total of 99,778-hectare grid cells, or equivalently 997.8 square kilometres, constitute the geographical scope of the city´s urban areas under study. In the far-right columns, the accumulation of heat demand by cost class, confirms the before-noticed tendencies of reductions primarily in high heat-demand density areas, where, in the FE2050 scenario, 26% of the total heat demand could be reached at marginal cost levels not exceeding 2.5 euro/GJ (9.0 euro/MWh), but where, in the BL2050 scenario, this number is sharply reduced to 12%. Still, even under the BL2050 scenario, no less than 41% of the total heat demand is assessed reachable at cost levels below 5 euro/GJ, which signifies a general preservation of sufficiently high heat demand concentrations for feasible heat distribution also in association with ambitious energy saving strategies. Noteworthy, from a network heat distribution perspective, the total value of the studied urban heat markets is approximately 20 billion euro.

For additional detail and reference regarding the criteria metric of renewable energy sources, which, as stated above, here is limited to biomass resources, Table 18 shows the total biomass potential of all the cities in 2050. The potential is given by the distance to the city centre (50 km and 100 km) and refers, on the one hand, to the reference scenario mainly elaborated in this report (labelled “Total”) and, on the other, to an alternative scenario here labelled “Biomass – PRIO”. By the label PRIO is indicated a so-called “conditioned” biomass potential that was prepared on the basis of the reference scenario in [65], and which adheres to the notion of sustainability by only considering agricultural and forestry residues, excluding round wood and bio commodities from which transport fuels may be produced.

As can be seen in Table 18, and as previously illustrated in Figure 23 above (Vienna map overview 2), Vienna benefits from the largest biomass capacity among the project cities. Out of the total 173.7 PJ/a potential of the city in its 100 km vicinity, 48% could be said to belong within the PRIO alternative, which also represents the most outstanding PRIO capacity. Dublin is the city that relatively suffers the most from a lack of biomass. Its potential in 2050 under the PRIO alternative would be 7.3 PJ/a, which is less than 3% of the total. This limited availability of biomass in the Irish capital, in combination with the city's 89%-dependency on fossil fuels (as Table 19 indicates), denotes again the special need for precaution and careful planning when looking for alternative sources and solutions for its H/C development plans. At the 100-kilometre distance setting, Munich, with 60%, and Rotterdam, with 34%, are the two project cities which hold the highest, and the lowest, ratios respectively regarding the quota between the PRIO alternative and the reference scenario (which, as should be mentioned, include municipal solid wastes in both cases).

TABLE 18. BIOMASS POTENTIALS FOR 2050 BY THE JRC ENSPRESO REFERENCE SCENARIO (TOTAL) AND CONDITIONED TO MEET SUSTAINABILITY CRITERIA FOCUSSING ON RESIDUAL BIO COMMODITIES ONLY (PRIO). SOURCES: [43, 65]

	Biomass potential 2050 (Enspreso REF)			
	Biomass - PRIO (50 km)	**Biomass - PRIO (100 km)**	**Biomass - Total (50 km)**	**Biomass - Total (100 km)**
Name	**[PJ/a]**	**[PJ/a]**	**[PJ/a]**	**[PJ/a]**
Bilbao	3.6	17.8	11.5	41.7
Bratislava	7.4	24.3	15.5	51.2
Dublin	1.8	7.3	4.7	18.6
Munich	25.5	81.2	42.9	134.9
Rotterdam	4.7	21.2	13.5	62.1
Vienna	18.4	83.7	38.9	173.7
Winterthur	11.1	43.7	21.3	81.2
Grand total	**72.4**	**279.4**	**148.2**	**563.3**
Grand total [TWh]	**20.1**	**77.6**	**41.2**	**156.5**

5.2. City ranking

The resulting data matrix for implementing the TOPSIS method, as presented in Table 19, reveals the performance of each city with respect to the structuring criteria that were most highly evaluated by the experts as important for achieving the goal (see reference [3] for the full detail on the AHP questionnaire and the associated expert responses). The results do not necessarily indicate that a low score means no possibilities of obtaining the goal, just that the relative suitability of the city is lower than that of the highest evaluated criteria.

Table 19 shows the performance or status of each city regarding each structuring criterion. In this table, higher values for those indicators labelled as forward and lower values for those measures labelled as reverse are preferable. For example, considering the heat demand density as a forward criterion, Munich is most apt for H/C decarbonisation, as its index is 46%, which is the highest among the project cities (keeping in mind the definition of this criterion being "the share of hectare cells out of the urban area total with heat demand densities above 120 TJ/km2 under the sEEnergies Frozen Efficiency scenario (FE2050)" (Table 3).

For another example, it is observed that with a value of 38.1 PJ/a, Rotterdam keeps the best condition in terms of the waste heat potential, as its tremendous annual volume of available waste heat provides a highly suitable foundation for expanding green heating systems. Additionally, the criterion of individual energy efficiency, which utilises the quota between the elaborated BL2050 and FE2050 scenario data for its definition (expressed as a number between 1 and 10 by classification, see further Table 3), was found on average at the value 3.8, but with two extreme cases: Bilbao at the value 1.0 and Dublin at the value 8.0. A value of 1.0 corresponds approximately to an individual energy efficiency potential of from zero up to 15%, a value of 2, between 15% and 20%, a value of 3, between 20% and 25% etc. The found average would correspond to an approximate potential of 25%, while the highest number (10) corresponds to efficiency potentials in the order of 60% to 70%, according to the used composite sEEnergies Index [49].

TABLE 19. THE DECISION DATA MATRIX OF THE DECARBONISATION PROBLEM CONSISTING OF TEN STRUCTURING CRITERIA AND SIX CONSIDERED PROJECT CITIES (WINTERTHUR IN PARENTHESIS TO INDICATE EXCLUSION FROM THE CITY RANKING DUE TO MISSING DATA FOR SEVERAL CRITERIA)

City/Criterion	City population	Heating index	Heat Demand Density	Individual energy efficiency	Structural energy efficiency	Dependency on fossil fuels	Potential for renewable sources	Potential for waste heat	Development of the built environment	Coverage of district heating
Bilbao	-34%	71	41%	1.0	86%	90%	41.7	8.3	16%	0%
Bratislava	-33%	100	41%	3.8*	47%	30%	51.2	4.5	18%	70%
Dublin	-2%	98	18%	8.0	22%	89%	18.6	8.3	29%	0%
Munich	27%	108	46%	4.0	65%	50%	134.9	8.7	7%	30%
Rotterdam	-17%	96	30%	3.0	41%	72%	62.1	38.1	24%	18%
Vienna	25%	99	45%	3.0	80%	46%	173.7	14.1	35%	39%
(Winterthur)	-	104	-	-	-	70%	81.2	-	-	20%
Average	**-6%**	**97**	**37%**	**3.8**	**57%**	**64%**	**80.5**	**13.7**	**21%**	**25%**

*The average of the other five cities.

Since the number of cities and criteria is high, it is difficult to distinguish which city has a better condition in all the measures bearing in mind their weights assigned by experts (as presented above in Table 4). The TOPSIS method, however, can systematically provide a ranking for the cities. The comparable, normalized, data matrix of the decarbonisation problem at hand, as well as the imaginary ideal and anti-ideal solutions, are provided for reference and transparency in Table 21 and Table 22 (in the Appendix).

The Euclidean distance of each city to the two ideal and anti-ideal solutions is presented in Table 20. As seen in the table, all cities have some distance to the ideal and to the anti-ideal solutions, meaning that none of the cities are representative of an absolute solution with superior performance in all the considered indicators. In other words, no city is “the best” in all the ten structuring criteria, which we again emphasise here, but are differently suited for different decarbonisation strategies depending on their unique local conditions.

TABLE 20. DISTANCE OF CITIES TO THE IDEAL AND ANTI-IDEAL SOLUTIONS

City	Distance to the ideal solution	Distance to the anti-ideal solution
Bilbao	0,186	0,099
Bratislava	0,135	0,147
Dublin	0,208	0,058
Munich	0,123	0,119
Rotterdam	0,145	0,107
Vienna	0,100	0,154

Figure 28 puts in view the cities' final ranking, where the more significant the TOPSIS score, the higher the rank. The ranking in Figure 28 reveals the performance of each city with respect to the structuring criteria that were most highly evaluated by the experts as important for achieving the goal. The results do not necessarily indicate that a low score means no possibilities of obtaining the goal, just that the relative suitability of the city/area/district is lower than that of the highest evaluated measures.

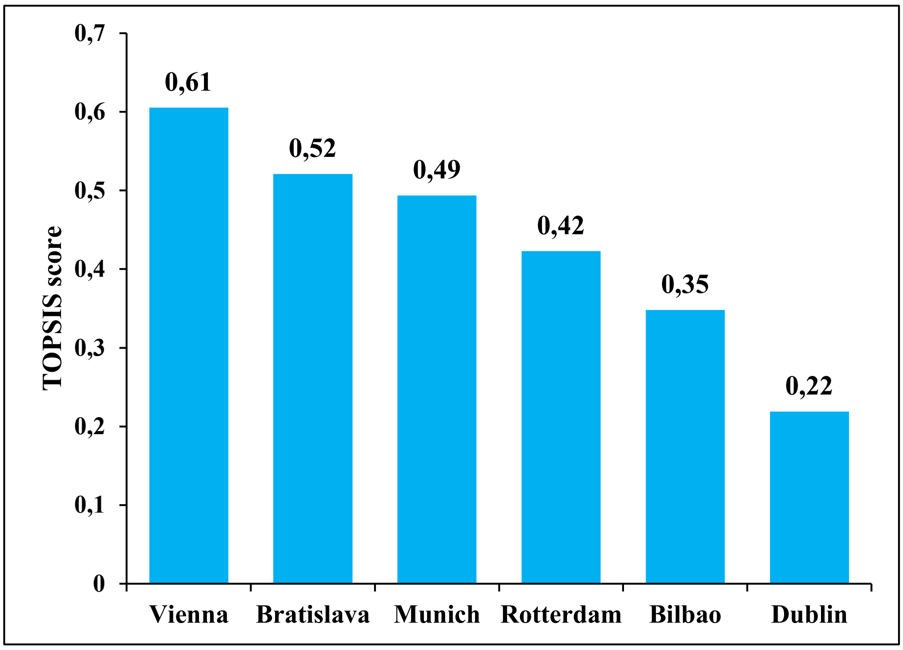


FIGURE 28. TOPSIS RANKING OF THE PARTICIPATING CITIES REGARDING THEIR SUITABILITY FOR DECARBONISATION OF URBAN HEATING AND COOLING SYSTEMS.

According to Figure 28 further, and thus based on the ten structuring criteria, their awarded weights, and their input data values, Vienna, among the six considered project cities (Winterthur not included in the TOPSIS ranking due to missing data for several criteria), may be said to have the highest suitability to decarbonize its heating and cooling system with a final TOPSIS ranking-score of 0.61. This means that considering all the criteria and their relative importance given by experts, the city's overall condition for H/C decarbonisation is the most promising among the six cities. Importantly, in this analysis is referred to by this annotation ("overall condition"), the overall city performance merely within the considered ten structuring criteria, and not beyond those.

For the further interpretation of these results, it is also relevant to keep in mind the expert opinions and the resulting weights that were awarded the different criteria. As was presented in Figure 3 above, the three criteria metrics of "structural energy efficiency", "coverage of district heating", and "potential of renewables sources", are, by order of magnitude, the three most crucial assessment criteria when aiming at decarbonising urban H/C systems.

In this perspective, Vienna's score on the structural energy efficiency metric (80%), which is regarded as very high and only second to the city of Bilbao (86%), has a significant impact on the final ranking-score. Vienna is also in possession of the widest current district heating coverage among the project cities (39%) next to Bratislava (70%), and holds, by a large amount, the highest potential for renewables (173.3 PJ/a) in comparison with the other project cities. Regarding the latter, the Vienna renewable energy potential is nearly 30% higher than that in the city of Munich (134.9 PJ/a), being the second-ranked city under this metric. These are examples of the underlying criteria dynamics that explain why TOPSIS dedicates the greatest final score to Vienna in its ranking. Bratislava (0.52) and Munich (0.49) are the second and third cities in this ranking, and the city of Dublin (0.22) is the last.

The main drivers for Dublin ending up with the lowest TOPSIS ranking-score in this analysis are, accordingly, that the city has the lowest of all scores in the main criteria metric with the highest weight, that of structural energy efficiency (22%), while simultaneously having the lowest scores concerning the criteria metrics next in weights; current district heating (0%) and renewable energy sources (18.6 PJ/a). However, being assigned a low rank in the TOPSIS method, does not necessarily mean that a city is completely void of opportunities for decarbonisation, it is merely an indication of its suitability with respect to such H/C decarbonisation strategies that are recognised as most important by expert opinion.

With that concluded, we would like to end this account in the particular recognition of the large urban waste heat recovery potentials that have already started to be harvested in a newly constructed district heating scheme in the city of Dublin, and in the general recognition of strategic heat planning as the key gateway to decarbonised, sustainable, and synergetic future urban heating and cooling systems.

6. Concluding remarks and recommendations for 2050

This report is an output from collaborative partner work within Work Package 2 (WP2) in the EU Horizon 2020 project Decarb City Pipes 2050 - Transition roadmaps to energy efficient, zero-carbon urban heating and cooling. The report constitutes the second part of a three-deliverable bundle which describes and accounts for the development of a coherent methodological framework to address multiple objectives associated with these deliverables.

The first account is the deliverable D2.5 report which, on the basis of input data gathered for ten structuring criteria within an Analytical Hierarchy Process (AHP) context, defines six decarbonisation design approaches based on three distinct urban typologies [3]. The second account – this report – presents quantified heating and cooling outlooks for 2050 based on the gathered criteria data for each of the project cities and performs, on this basis and further by application of the TOPSIS ranking method, a cross-city synthesis for the project cities. With reference to its results and outputs, this account also concludes general city recommendations for urban H/C supplies and demands in 2050. The third account, the D2.7 deliverable report, presents a set of complementary recommendations from other perspectives for decarbonizing urban H/C. Noteworthy, by this disposition, the reader is referred to the third and final bundle-account for the proper discussion of the outcomes from this report and the preceding D2.5 report.

Within in the Decarb City Pipes 2050 project, six European cities aim to create actionable and spatially differentiated *Transition Roadmaps* to decarbonise their heating and cooling sectors in 2050. The six cities are Bilbao (Spain), Dublin (Ireland), Munich (Germany), Rotterdam (the Netherlands), Vienna (Austria), and Winterthur (Switzerland). In these cities, Local Working Groups (LWG´s), consisting of representatives from various local institutions, from city administrations, consultancies, and utilities, are organising the work to address this challenge. A seventh city, Bratislava (Slovakia), is also part of the project as participant in capacity building activities and by contributing experience to peer-to-peer exchanges. Within the coherent methodological framework, all seven cities have been considered to the extent possible considering availability of public, continental level, hence, directly comparable and replicable input data.

The objective and main purport of the coherent framework approach is to develop a useful analytical architecture for cities in Europe, thus not exclusively for the seven project cities, whereby to facilitate first-order quantification, arrangement, and mapping, of likely future year conditions upon which basis the demand for further in-depth analyses can be identified. The framework represents a straight-forward, easy-to-use, “machinery” for future year assessments in any European city since it deliberately entails publicly available EU-level data (to the extent possible) and well-established and documented analytical instruments.

For the participating project cities, which all are developing city-specific data and arranging highly detailed spatial analyses of their own, as part of project activities, the coherent framework analysis is intended to bring additional value with its focus on future year input data (which often is unavailable). Knowledge wise, the framework aims to support the project cities by the introduction and application of several concepts (such as urban typologies with associated decarbonisation design approaches), the quantification of local conditions by ten directly comparable input data parameters (the structuring criteria) and the associated cross-city synthesis, and, lastly, by a set of concluding recommendations for a future transition.

Regarding the particular results presented in this report, that is regarding the heating and cooling outlooks for 2050 and the cross-city synthesis, it may be appropriate with a few final remarks. Firstly, the structuring criteria average, relative to which each city´s respective metric value was compared, was here the average only of the seven studied cities themselves, and not – which could be very interesting to explore in future works – an EU-wide average or similar. If criteria parameter averages were to be established on the basis of a larger number of cities, say a couple of thousand cities with different sizes, climatic conditions, population distributions etc., the framework results would likely be different and, in fact, more representative and robust.

Secondly, in this first application of the coherent framework, ten structuring criteria parameters were elaborated. Why were there not more? Or fewer? The answer to these questions is mainly the corresponding publicly-available access to EU-scoped underlying input data, which was a prerequisite for the inclusion of any plausible structuring criteria. If one were to ask the related question: why these selected 10 structuring criteria, why not others? the answer would be similar. As already noted at several places in the report, it is worth mentioning again that the quality and accuracy of the used input data, of any used input data, will of course influence the results accordingly. For the input data used in the presented framework, some ambiguity exists with reference to the criteria “Dependency of fossil fuels” (vaguely stated on some occasions) and with reference to the criteria “Potential for renewable sources” (which here is represented by biomass only).

Finally, as the overall objective of the Decarb City Pipes 2050 project is to accelerate the process of urban transition to energy efficient and zero-carbon heating and cooling solutions by strengthening planning and implementation capacities within cities, this report presented in its introductory section an exposé and discussion of a number of so-called *Key Concepts* associated with such urban transitions. As promised in the above section, the elaborated key concepts are listed here, among the concluding remarks, for general orientation and recollection. Thus, in alphabetical order:

- ***Best Available Organisation (BAO)***
- ***Best Available Technology (BAT)***
- ***Critical Choices***
- ***Directed Change***
- ***Energy Efficiency***
- ***Energy System Integration***
- ***Excess Heat Recovery Rate***
- ***Excess Heat Utilisation Rate***
- ***Green and Circular Economies***
- ***Heat Demand Density (Ground Density)***
- ***Individual Energy Efficiency Measures***

- ***Industrial Symbiosis***
- ***Local Conditions***
- ***Parallel and Serial Supply Structures***
- ***Path Dependency***
- ***Population Development Trend***
- ***Renewable Energy***
- ***Strategic Heat Planning***
- ***Structural Energy Efficiency Measures***
- ***Technology Lock-in***
- ***Urbanisation Rate***

Appendix subsection 8.3 presents and discusses several specific and thematical recommendations for cities' H/C supplies & demands in 2050, partly based on the unique local conditions in seven project cities, partly based on framework findings as well as on other references and sources. The recommendations for 2050 are presented first with reference to cities' heating and cooling supplies and demands in 2050 (appendix subsection 8.3.1), secondly with reference to strategic heat planning (appendix subsection 8.3.2), and finally with reference to some elementary heating and cooling sector transition measures (appendix subsection 8.3.3).

7. References

1. EC, *COM(2016) 51 final. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. An EU Strategy on Heating and Cooling. {SWD(2016) 24 final}*. 2016: European Commission, Brussels.
2. Eurostat, *SHARES (Renewables). Energy from renewable sources. SHARES summary results 2019*. 2019: Eurostat. Your key to European statistics. European Commission. Luxembourg. Available at (2021-06-01): https://ec.europa.eu/eurostat/web/energy/data/shares.
3. Lichtenwöhrer, P., et al., *Report on decarbonisation design approaches based on urban typologies. Deliverable D2.5*. 2022: Decarb City Pipes 2050 - Transition roadmaps to energy efficient, zero-carbon urban heating and cooling. Project No. 893509.
4. Persson, U., M.S. Atabaki, and L. Sánchez-García, *Recommendations for cities' H/C supplies & demands in 2050. Deliverable D2.7*. 2022 (to be published): Decarb City Pipes 2050 - Transition roadmaps to energy efficient, zero-carbon urban heating and cooling. Project No. 893509. (planned publication during the autumn of 2022).
5. EU, *Directive (EU) 2018/2001 ot the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources*. 2018, European Parliament and the Council: Brussels.
6. EC, *The European Green Deal. COM(2019) 640 final*. 2019: European Commission. .
7. EC, *A Clean Planet for all. A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy COM(2018) 773 final. 28 November 2018*. 2018: European Commission.
8. EC, *COM(2014) 398 final/2. Towards a circular economy: A zero waste programme for Europe*. 2014: European Commission, Brussels. .
9. Persson, U., et al., *Heat Roadmap Europe: Heat distribution costs.* Energy, 2019. **176**: p. 604-622.
10. Energistyrelsen, *Individual Heating Plants and Energy Transport: Technology Data for Energy Plants, May 2012*. 2012: Energistyrelsen (Danish Energy Agency).
11. HRE. *Heat Roadmap Europe - A low-carbon heating and cooling strategy for Europe. Available at (2018-11-21): (https://heatroadmap.eu/)*. 2018.
12. Connolly, D., et al., *Heat Roadmap Europe 2050 - First pre-study for EU27.* Department of Development and Planning, Aalborg University. http://vbn.aau.dk/da/publications/heat-roadmap-europe-2050%28a855df3d-d211-45db-80de-94ee528aca8d%29.html, 2012.
13. Connolly, D., et al., *Heat Roadmap Europe 2: Second Pre-Study for the EU27.* Department of Development and Planning, Aalborg University. https://vbn.aau.dk/en/publications/heat-roadmap-europe-2-second-pre-study-for-the-eu27, 2013.
14. Persson, U., *District heating in future Europe: Modelling expansion potentials and mapping heat synergy regions*. 2015, Energy and Environment, Chalmers University of Technology: Dissertation Thesis. Series Nr: 3769. Göteborg.
15. Persson, U. and S. Werner, *District heating in sequential energy supply.* Applied Energy, 2012. **95**: p. 123-131.
16. Collins, J.F., *The History of District Heating*, in *District Heating*. 1959: pp. 154-161. Available at (2014-10-18): (http://www.districtenergy.org/assets/pdfs/HistoryDistrictEnergy1959.pdf).
17. Lund, H., et al., *4th Generation District Heating (4GDH): Integrating smart thermal grids into future sustainable energy systems.* Energy, 2014. **68**(0): p. 1-11.
18. Lund, H., et al., *The status of 4th generation district heating: Research and results.* Energy, 2018. **164**: p. 147-159.
19. Werner, S., *Network configurations for implemented low-temperature district heating.* Energy, 2022: p. 124091.
20. Lund, H., et al., *Perspectives on Fourth and Fifth Generation District Heating.* Energy, 2021: p. 120520.
21. Meesenburg, W., et al., *Economic feasibility of ultra-low temperature district heating systems in newly built areas supplied by renewable energy.* Energy, 2020. **191**: p. 116496.

22. Averfalk, H., et al., *Low-Temperature District Heating Implementation Guidebook : Final Report of IEA DHC Annex TS2. Implementation of Low-Temperature District Heating Systems*. 2021, Fraunhofer IRB Verlag: Stuttgart. p. 201.
23. Djørup, S.R., et al., *Definition & Experiences of Strategic Heat Planning: Handbook I.* 2019: Hotmaps – Heating and Cooling Open Source Tool for Mapping and Planning of Energy Systems (No. 723677). Aalborg University, Denmark. Available at (2021-06-21): https://www.hotmaps-project.eu/wp-content/uploads/2019/04/Handbook-I.pdf.
24. Kicherer, N., P. Lorenzen, and H. Schäfers, *Design of a District Heating Roadmap for Hamburg.* Smart Energy, 2021: p. 100014.
25. Federal Ministry for Economic Affairs and Energy, *Baden-Württemberg introduces mandatory heat planning for municipalities*. 2020: German Energy Solutions. Available at (2021-06-21): https://www.german-energy-solutions.de/GES/Redaktion/EN/News/2020/20200219-baden-wuerttemberg-heat-planning.html.
26. Lumbreras, M., et al., *Design of district heating networks in built environments using GIS: A case study in Vitoria-Gasteiz, Spain.* Journal of Cleaner Production, 2022. **349**: p. 131491.
27. sEEnergies Open Data Hub, *sEEnergies Open Data Hub. Referenced dataset: "D5 2 UA Demographical attributes"*. 2022: Europa-Universität Flensburg, ArcGIS Online. sEEnergies: Quantification of synergies between Energy Efficiency first principle and renewable energy systems. Available at (2022-05-28): (https://s-eenergies-open-data-euf.hub.arcgis.com/search?categories=d5.2).
28. Wiechers, E., B. Möller, and U. Persson, *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 (1.2)*. 2020: sEEnergies - Quantification of Synergies between Energy Efficiency First Principle and Renewable Energy Systems. Horizon 2020 Project No. 846463. DOI: https://doi.org/10.5281/zenodo.3902134.
29. CDF, *Super Decisions software*. 2022: The Creative Decisions Foundation. Available from [cited 2022-08-26]: https://www.superdecisions.com/.
30. Hotmaps, *Hotmaps - The open source mapping and planning tool for heating and cooling*. 2018: Available at (2018-08-31): http://www.hotmaps-project.eu/
31. ReUseHeat, *Recovery of Urban Waste Heat*. 2018: European Union's H2020 Programme under grant agreement 767429. Available (2021-06-21): https://www.reuseheat.eu/.
32. sEEnergies, *sEEnergies - Quantification of Synergies between Energy Efficiency First Principle and Renewable Energy Systems*. 2020: Horizon 2020 Project No. 846463. Available at (2021-06-21): https://www.seenergies.eu/.
33. Möller, B., et al., *The Pan-European Thermal Atlas (Peta, version 5.2)*. 2022, Developed as part of the sEEnergies project. Europa-Universität Flensburg: Flensburg. Available at (2022-10-01): https://euf.maps.arcgis.com/apps/webappviewer/index.html?id=8d51f3708ea54fb9b732ba0c94409133.
34. Moreno, D., S. Nielsen, and U. Persson, *The European Waste Heat Map*. 2022: ReUseHeat project – Recovery of Urban Excess Heat. Last update: 2022-05-31. Available at: https://tinyurl.com/2wvh7ud7.
35. Elbersen, B., et al., *The JRC-EU-TIMES model : bioenergy potentials for EU and neighbouring countries*. 2015, Joint Research Centre, Institute for Energy and Transport: Publications Office.
36. Peta 4.3, *Pan-European Thermal Atlas 4.3 (Peta 4.3)*. 2018: Europa-Universität Flensburg, ArcGIS Online. Heat Roadmap Europe - A low-carbon heating and cooling strategy for Europe. Available at (2018-11-22): (https://heatroadmap.eu/peta4/).
37. ES, *Administrative units/Statistical units*. 2022, Eurostat, Luxembourg. Available at (2022-09-12): (https://ec.europa.eu/eurostat/web/gisco/geodata/reference-data/administrative-units-statistical-units).
38. Copernicus, *CORINE Land Cover. Version: CLC2018_CLC2018_V2018_20*. 2018: Copernicus: Europe's eyes on Earth. Available at (2018-11-22): (https://land.copernicus.eu/pan-european/corine-land-cover).
39. sEEnergies Open Data Hub, *sEEnergies Open Data Hub. Referenced dataset: "D5 1 District Heating Areas"*. 2022: Europa-Universität Flensburg, ArcGIS Online. sEEnergies: Quantification of synergies

between Energy Efficiency first principle and renewable energy systems. Available at (2022-05-28): (https://s-eenergies-open-data-euf.hub.arcgis.com/search?categories=d5.1).
40. Manz, P., et al., *Decarbonizing District Heating in EU-27 + UK: How Much Excess Heat Is Available from Industrial Sites?* Sustainability, 2021. **13**(3): p. 1439.
41. Fleiter, T., et al., *D5.1: Excess heat potentials of industrial sites in Europe (Revised version). Documentation on excess heat potentials of industrial sites including open data file with selected potentials*. 2020: sEEnergies - Quantification of synergies between Energy Efficiency first principle and renewable energy systems. DOI: (https://doi.org/10.5281/zenodo.4785411).
42. Madsen, A., et al., *H/C plans of cities with cross-city synthesis. Deliverable D3.3*. 2022: Decarb City Pipes 2050 - Transition roadmaps to energy efficient, zero-carbon urban heating and cooling. Project No. 893509.
43. Nijs, W., *JRC-EU-TIMES - JRC TIMES energy system model for the EU (1.1.1) [Data set: 2019 ENSPRESO_BIOMASS.xlsx]. Zenodo. https://doi.org/10.5281/zenodo.3544900*. 2019.
44. sEEnergies Open Data Hub, *sEEnergies Open Data Hub. Referenced dataset: "UA Future DH Potentials"*. 2022: Europa-Universität Flensburg, ArcGIS Online. sEEnergies: Quantification of synergies between Energy Efficiency first principle and renewable energy systems. Available at (2022-05-28): (https://s-eenergies-open-data-euf.hub.arcgis.com/search?categories=seenergies_heat).
45. NOAA, *Global Surface Hourly (Integrated Surface Dataset)*. 2001: NOAA National Centers for Environmental Information.
46. sEEnergies Open Data Hub, *sEEnergies Open Data Hub. Referenced datasets: "BL2015 HD100 total", "BL2050 HD100 total", and "FE2050 HD100 total"*. 2022: Europa-Universität Flensburg, ArcGIS Online. sEEnergies: Quantification of synergies between Energy Efficiency first principle and renewable energy systems. Available at (2022-05-28): (https://s-eenergies-open-data-euf.hub.arcgis.com/search?categories=seenergies_buildings).
47. sEEnergies Internal, *sEEnergies Internal working datasets. Referenced datasets: "EU_total_floor_area_2015" and "EU_total_floor_area_2050"*. 2022: Europa-Universität Flensburg, ArcGIS Online. sEEnergies: Quantification of synergies between Energy Efficiency first principle and renewable energy systems.
48. sEEnergies Open Data Hub, *sEEnergies Open Data Hub. Referenced datasets: "D5 7 sEEnergies Index"*. 2022: Europa-Universität Flensburg, ArcGIS Online. sEEnergies: Quantification of synergies between Energy Efficiency first principle and renewable energy systems. Available at (2022-05-28): (https://s-eenergies-open-data-euf.hub.arcgis.com/search?categories=seenergies_index).
49. Möller, B., et al., *D5.7: Spatial models and spatial analytics results*. 2022: sEEnergies - Quantification of Synergies between Energy Efficiency First Principle and Renewable Energy Systems. Horizon 2020 Project No. 846463. Work in progress: Expected to be publicly available during spring/summer 2022.
50. sEEnergies Open Data Hub, *sEEnergies Open Data Hub. Referenced datasets: "BL2050 DHDCC" and "FE2050 DHDCC"*. 2022: Europa-Universität Flensburg, ArcGIS Online. sEEnergies: Quantification of synergies between Energy Efficiency first principle and renewable energy systems. Available at (2022-05-28): (https://s-eenergies-open-data-euf.hub.arcgis.com/search?categories=seenergies_heat).
51. Saaty, R.W., *The analytic hierarchy process—what it is and how it is used*. 1987: Mathematical Modelling. 9(3): p. 161-176.
52. Väisänen, S., et al., *Using a multi-method approach for decision-making about a sustainable local distributed energy system: A case study from Finland.* Journal of Cleaner Production, 2016. **137**: p. 1330-1338.
53. Aryanpur, V., et al., *An overview of energy planning in Iran and transition pathways towards sustainable electricity supply sector.* Renewable and Sustainable Energy Reviews, 2019. **112**: p. 58-74.
54. Baležentis, T. and D. Streimikiene, *Multi-criteria ranking of energy generation scenarios with Monte Carlo simulation.* Applied Energy, 2017. **185**: p. 862-871.
55. Karahalios, H., *The application of the AHP-TOPSIS for evaluating ballast water treatment systems by ship operators.* Transportation Research Part D: Transport and Environment, 2017. **52**: p. 172-184.
56. Lichtenwöhrer, P. and H. Hemis, *Report on data availability, data sovereignty, quality and exchange in the participating cities and policy recommendations. Deliverable D2.4*. 2022: Decarb City Pipes

2050 - Transition roadmaps to energy efficient, zero-carbon urban heating and cooling. Project No. 893509.

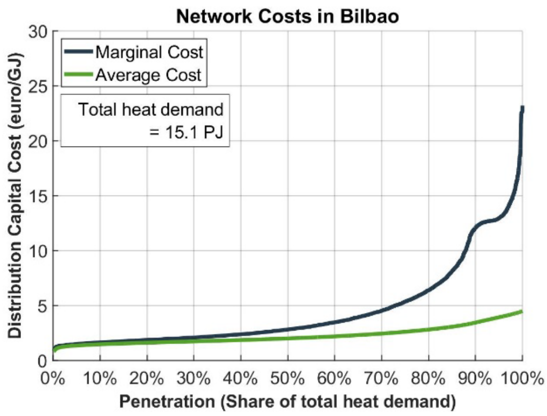
57. Wiechers, E., B. Möller, and U. Persson, *D5.5: Geographic layers that illustrate future energy efficiency potentials: Second set of map layers (future years scenarios for 2030 and 2050)*. 2022: sEEnergies - Quantification of Synergies between Energy Efficiency First Principle and Renewable Energy Systems. Horizon 2020 Project No. 846463. Work in progress: Expected to be publicly available during spring/summer 2022.
58. Maya-Drysdale, D.W., et al., *Energy Efficiency 2050 Roadmap for Europe: A cost-effective and energy-efficient strategy for decarbonising.* 2022: sEEnergies - Quantification of Synergies between Energy Efficiency First Principle and Renewable Energy Systems. Horizon 2020 Project No. 846463. Available at (2022-10-25): https://vbn.aau.dk/en/publications/energy-efficiency-2050-roadmap-for-europe-a-cost-effective-and-en.
59. EC, *Atlas of Geothermal Resources in Europe, Publication EUR 17811*. 2002, European Commission: Luxembourg. Available at (2021-06-27): https://op.europa.eu/en/publication-detail/-/publication/9003d463-03ed-4b0e-87e8-61325a2d4456.
60. Capros, P., et al., *Energy-system modelling of the EU strategy towards climate-neutrality.* Energy Policy, 2019. **134**: p. 110960.
61. Capros, P., et al., *Supplementary material for the paper "Energy-system modelling of the EU strategy towards climate-neutrality".* Energy Policy, 2019. **134**: p. 110960.
62. Persson, U. and S. Werner, *Heat distribution and the future competitiveness of district heating.* Applied Energy, 2011. **88**: p. 568-576.
63. Gondhalekar, D. and T. Ramsauer, *Nexus City: Operationalizing the urban Water-Energy-Food Nexus for climate change adaptation in Munich, Germany.* Urban Climate, 2017. **19**: p. 28-40.
64. Lenhart, J., B. van Vliet, and A.P.J. Mol, *New roles for local authorities in a time of climate change: the Rotterdam Energy Approach and Planning as a case of urban symbiosis.* Journal of Cleaner Production, 2015. **107**: p. 593-601.
65. Braungardt, S., et al., *Renewable Heating and Cooling Pathways, Measures and Milestones for the implementation of the recast Renewable Energy Directive and full decarbonisation by 2050 (ENER C1 2019-482). Expected publication by end of 2022 or early 2023.* To be published: Directorate-General for Energy, European Commission, Brussels.
66. SFOE, *Thematic geoportal - map.energie.admin.ch. Thermal networks: demand from residential and commercial buildings (Heat Demand Home And Services). Geodatensatz: Thermische Netze: Wärme- und Kälteangebot, Thermische Netze: Nachfrage Wohn- und Dienstleistungsgebäude, Thermische Netze: Nachfrage Industrie. Geodatenmodell Version: 1.0, Datum: 11.06.2019*. 2019: Swiss Federal Office of Energy (SFOE). Available at (2020-07-25): https://data.geo.admin.ch/ch.bfe.fernwaerme-nachfrage_wohn_dienstleistungsgebaeude/.
67. Persson, U., et al., *H/C outlook 2050 of cities with cross-city synthesis. Deliverable D2.6*. 2022: Decarb City Pipes 2050 - Transition roadmaps to energy efficient, zero-carbon urban heating and cooling. Project No. 893509.
68. Geonames, *The GeoNames geographical database is available for download free of charge under a creative commons attribution license*. 2020: St. Gallen, Switzerland. Available at (2020-08-25): https://www.geonames.org/.
69. Persson, U., et al., *D4.5 District heating investment costs and allocation of local resources for EU28 in 2030 and 2050*. 2021: sEEnergies - Quantification of Synergies between Energy Efficiency First Principle and Renewable Energy Systems. Horizon 2020 Project No. 846463. https://doi.org/10.5281/zenodo.4892271.
70. Korberg, A.D., et al., *On the feasibility of direct hydrogen utilisation in a fossil-free Europe.* International Journal of Hydrogen Energy, 2022.
71. Bertelsen, N., et al., *Integrating low-temperature renewables in district energy systems: Guidelines for policy makers*. 2021: International Renewable Energy Agency. Aalborg University, Denmark. Available at (2021-06-21): https://vbn.aau.dk/en/publications/integrating-low-temperature-renewables-in-district-energy-systems.

72. Lefrère, O., *Guide to Heat Mapping*. 2019: WP.T3 D1.1 Guide to Heat Mapping. HeatNet NWE project, Interreg North-West Europe programme. Available at (2021-06-21): https://www.nweurope.eu/media/8106/20190826-_-wp-t3-_-d11-_-guide-to-heatmapping-_-final.pdf.
73. sEEnergies Open Data Hub, *sEEnergies Open Data Hub*. 2020: Europa-Universität Flensburg, ArcGIS Online. sEEnergies: Quantification of synergies between Energy Efficiency first principle and renewable energy systems. Available at (2020-02-24): (https://tinyurl.com/sEEnergies-Hub).
74. Copernicus. 2022: Europe's eyes on Earth. Available at (2022-11-30): (https://www.copernicus.eu/en).
75. Eurostat, *Your key to European Statistics*. 2018, Eurostat, European Commission. Luxembourg. Available at (2018-10-15): (https://ec.europa.eu/eurostat/data/database?node_code=hid_tsdpc240).
76. UN, *World Urbanization Prospects: The 2018 Revision, Online Edition.* 2018: United Nations, Department of Economic and Social Affairs, Population Division. Available at (2020-08-30): https://population.un.org/wpp/. .

8. Appendix

8.1. City data for Frozen efficiency 2050 scenario

8.1.1. Bilbao



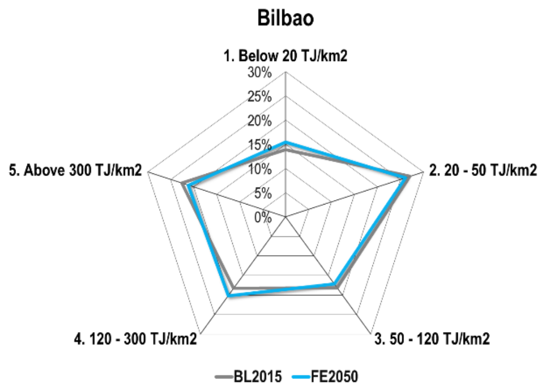


FIGURE 29. MARGINAL AND AVERAGE DISTRIBUTION CAPITAL COST LEVELS AND THE CORRESPONDING DISTRICT HEAT MARKET SHARES IN BILBAO FOR FE2050 [€/GJ] (LEFT). COST LEVELS REFLECT COSTS FOR BOTH DISTRIBUTION AND SERVICE PIPES. AT RIGHT, RADAR DIAGRAM WITH RELATIVE SHARES INDICATING THE DISTRIBUTION OF TOTAL CITY HEAT DEMAND BY FIVE HEAT DEMAND DENSITY CLASSES (CURRENT YEAR INCLUDED FOR REFERENCE (BL2015)).

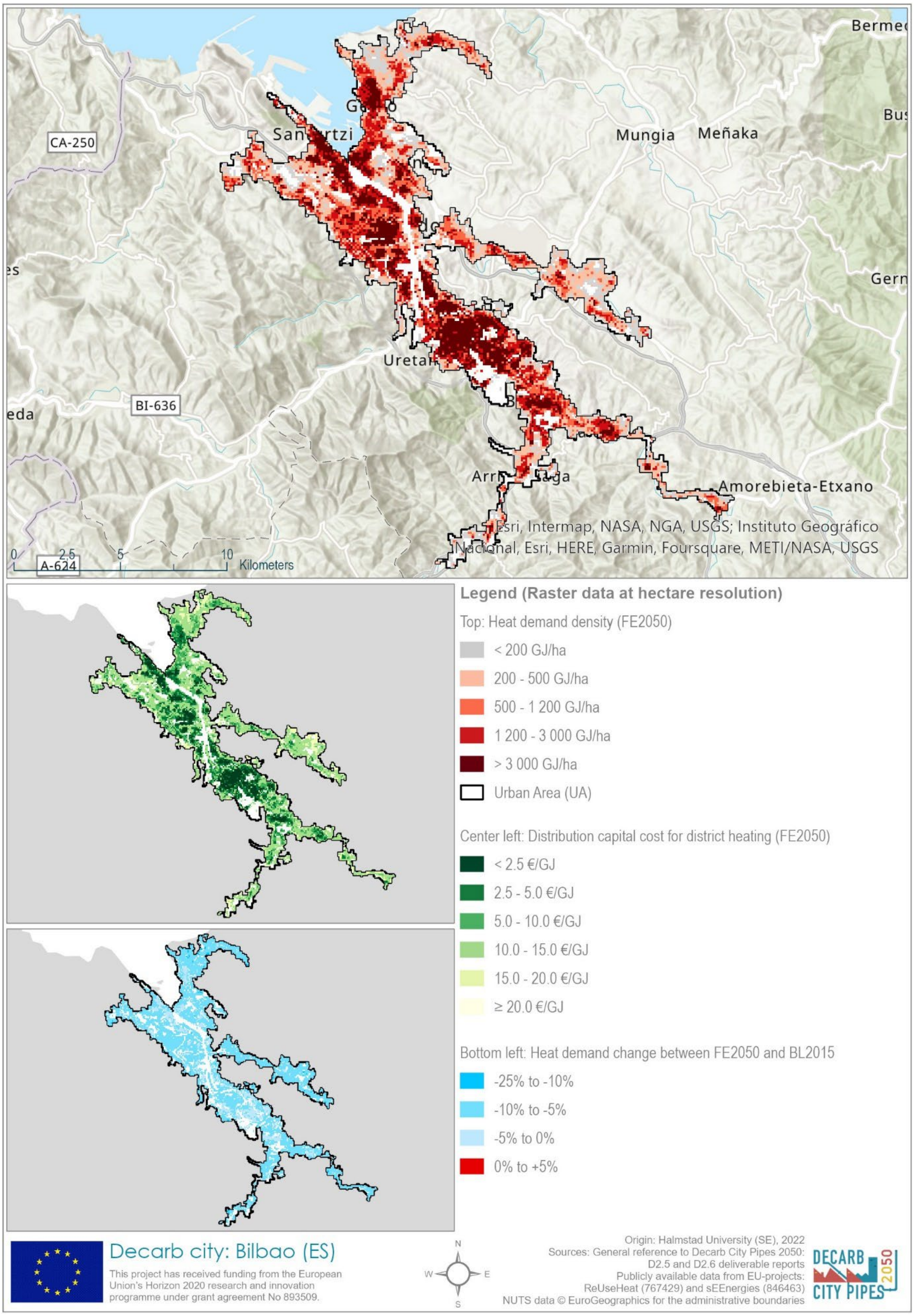


FIGURE 30. BILBAO MAP OVERVIEW 3: HEAT DEMAND DENSITY IN 2050 (FROZEN EFFICIENCY), DISTRIBUTION CAPITAL COST FOR DISTRICT HEATING IN 2050 (FROZEN EFFICIENCY), AND RELATIVE HEAT DEMAND CHANGE BETWEEN FROZEN EFFICIENCY 2050 AND BASELINE 2015. SOURCES: [27, 46, 50].

8.1.2. Bratislava

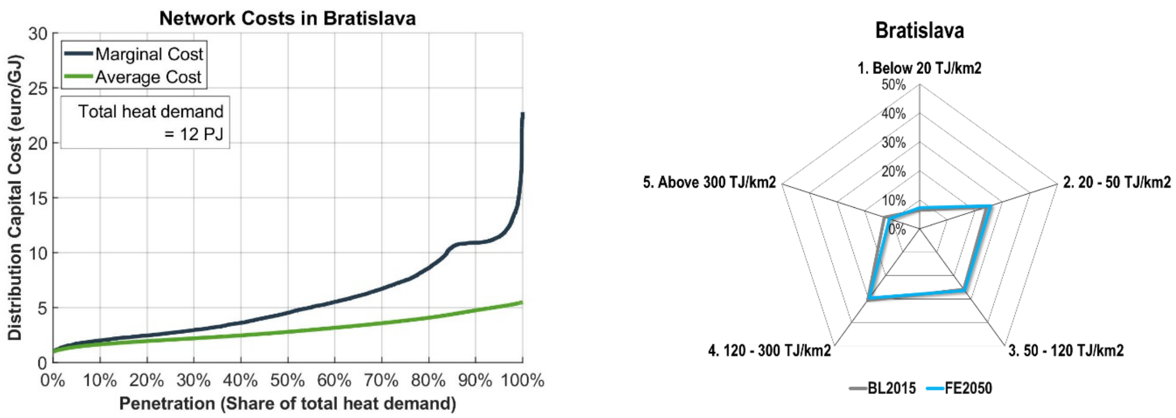


FIGURE 31. MARGINAL AND AVERAGE DISTRIBUTION CAPITAL COST LEVELS AND THE CORRESPONDING DISTRICT HEAT MARKET SHARES IN BRATISLAVA FOR FE2050 [€/GJ] (LEFT). COST LEVELS REFLECT COSTS FOR BOTH DISTRIBUTION AND SERVICE PIPES. AT RIGHT, RADAR DIAGRAM WITH RELATIVE SHARES INDICATING THE DISTRIBUTION OF TOTAL CITY HEAT DEMAND BY FIVE HEAT DEMAND DENSITY CLASSES (CURRENT YEAR INCLUDED FOR REFERENCE (BL2015)).

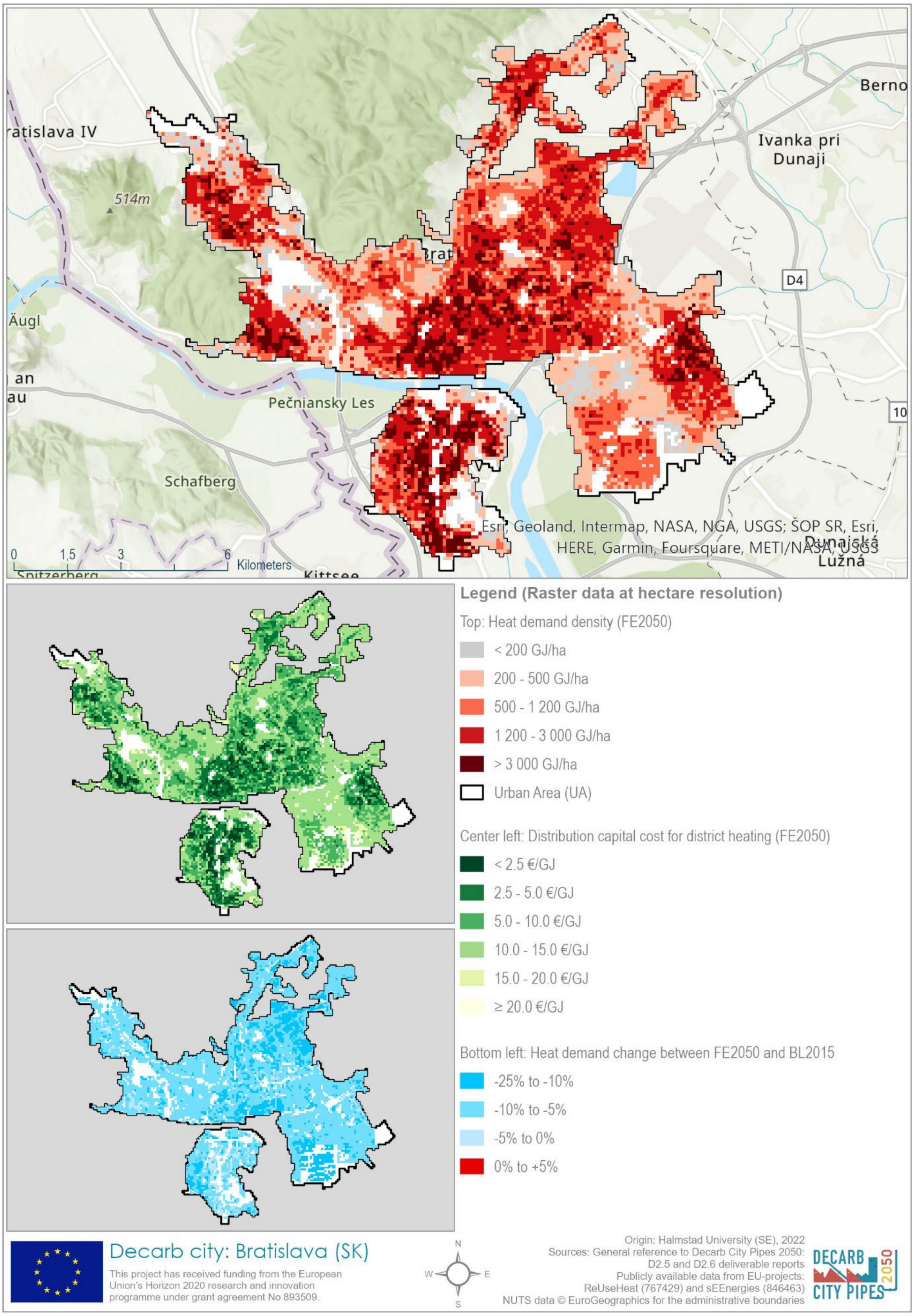


FIGURE 32. BRATISLAVA MAP OVERVIEW 3: HEAT DEMAND DENSITY IN 2050 (FROZEN EFFICIENCY), DISTRIBUTION CAPITAL COST FOR DISTRICT HEATING IN 2050 (FROZEN EFFICIENCY), AND RELATIVE HEAT DEMAND CHANGE BETWEEN FROZEN EFFICIENCY 2050 AND BASELINE 2015. SOURCES: [27, 46, 50].

8.1.3. Dublin

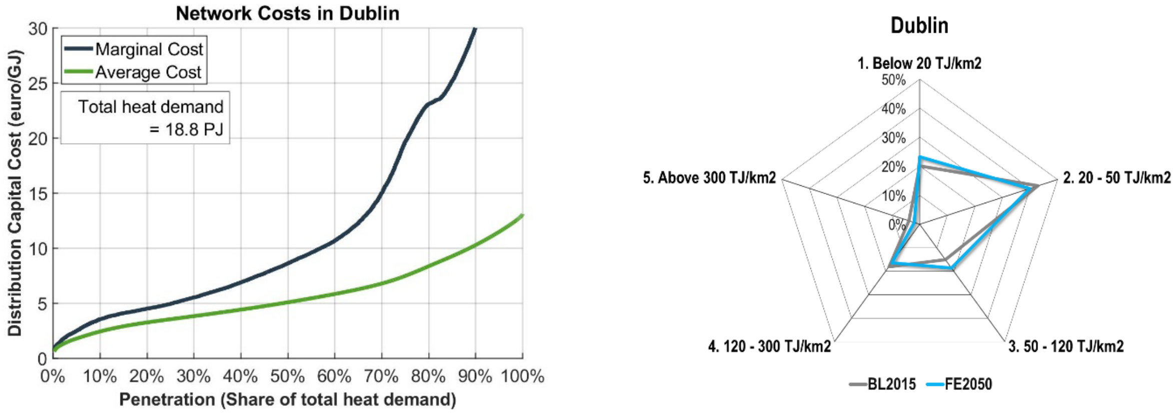


FIGURE 33. MARGINAL AND AVERAGE DISTRIBUTION CAPITAL COST LEVELS AND THE CORRESPONDING DISTRICT HEAT MARKET SHARES IN DUBLIN FOR FE2050 [€/GJ] (LEFT). COST LEVELS REFLECT COSTS FOR BOTH DISTRIBUTION AND SERVICE PIPES. AT RIGHT, RADAR DIAGRAM WITH RELATIVE SHARES INDICATING THE DISTRIBUTION OF TOTAL CITY HEAT DEMAND BY FIVE HEAT DEMAND DENSITY CLASSES (CURRENT YEAR INCLUDED FOR REFERENCE (BL2015)).

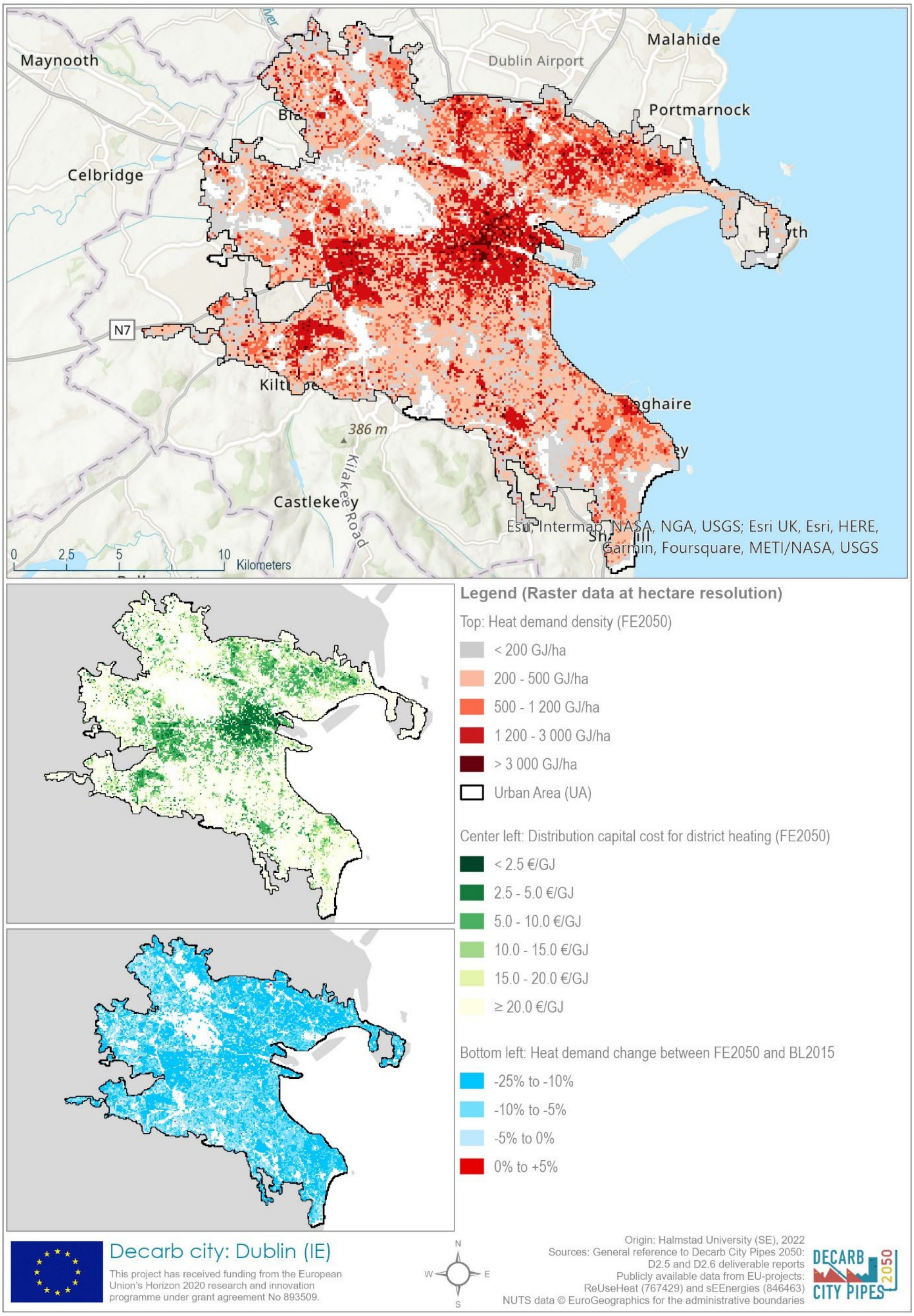


FIGURE 34. DUBLIN MAP OVERVIEW 3: HEAT DEMAND DENSITY IN 2050 (FROZEN EFFICIENCY), DISTRIBUTION CAPITAL COST FOR DISTRICT HEATING IN 2050 (FROZEN EFFICIENCY), AND RELATIVE HEAT DEMAND CHANGE BETWEEN FROZEN EFFICIENCY 2050 AND BASELINE 2015. SOURCES: [27, 46, 50].

8.1.4. Munich

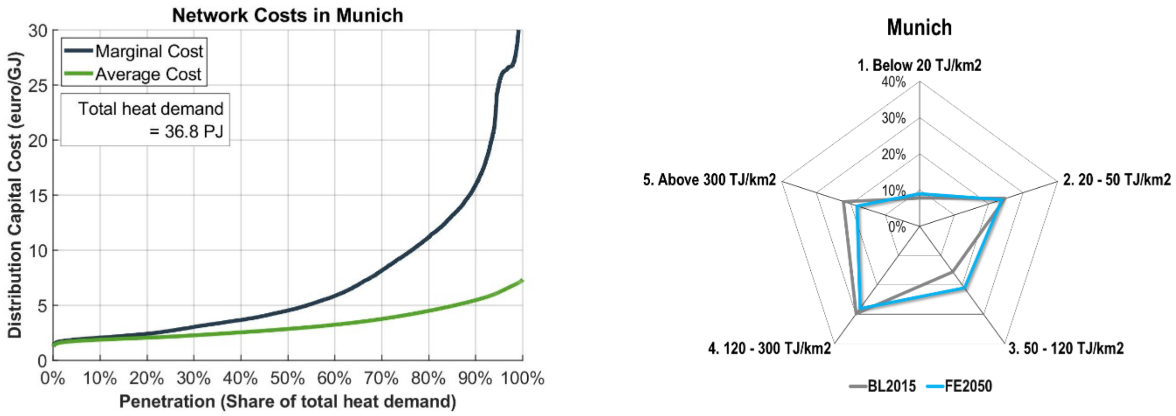


FIGURE 35. MARGINAL AND AVERAGE DISTRIBUTION CAPITAL COST LEVELS AND THE CORRESPONDING DISTRICT HEAT MARKET SHARES IN MUNICH FOR FE2050 [€/GJ] (LEFT). COST LEVELS REFLECT COSTS FOR BOTH DISTRIBUTION AND SERVICE PIPES. AT RIGHT, RADAR DIAGRAM WITH RELATIVE SHARES INDICATING THE DISTRIBUTION OF TOTAL CITY HEAT DEMAND BY FIVE HEAT DEMAND DENSITY CLASSES (CURRENT YEAR INCLUDED FOR REFERENCE (BL2015)).

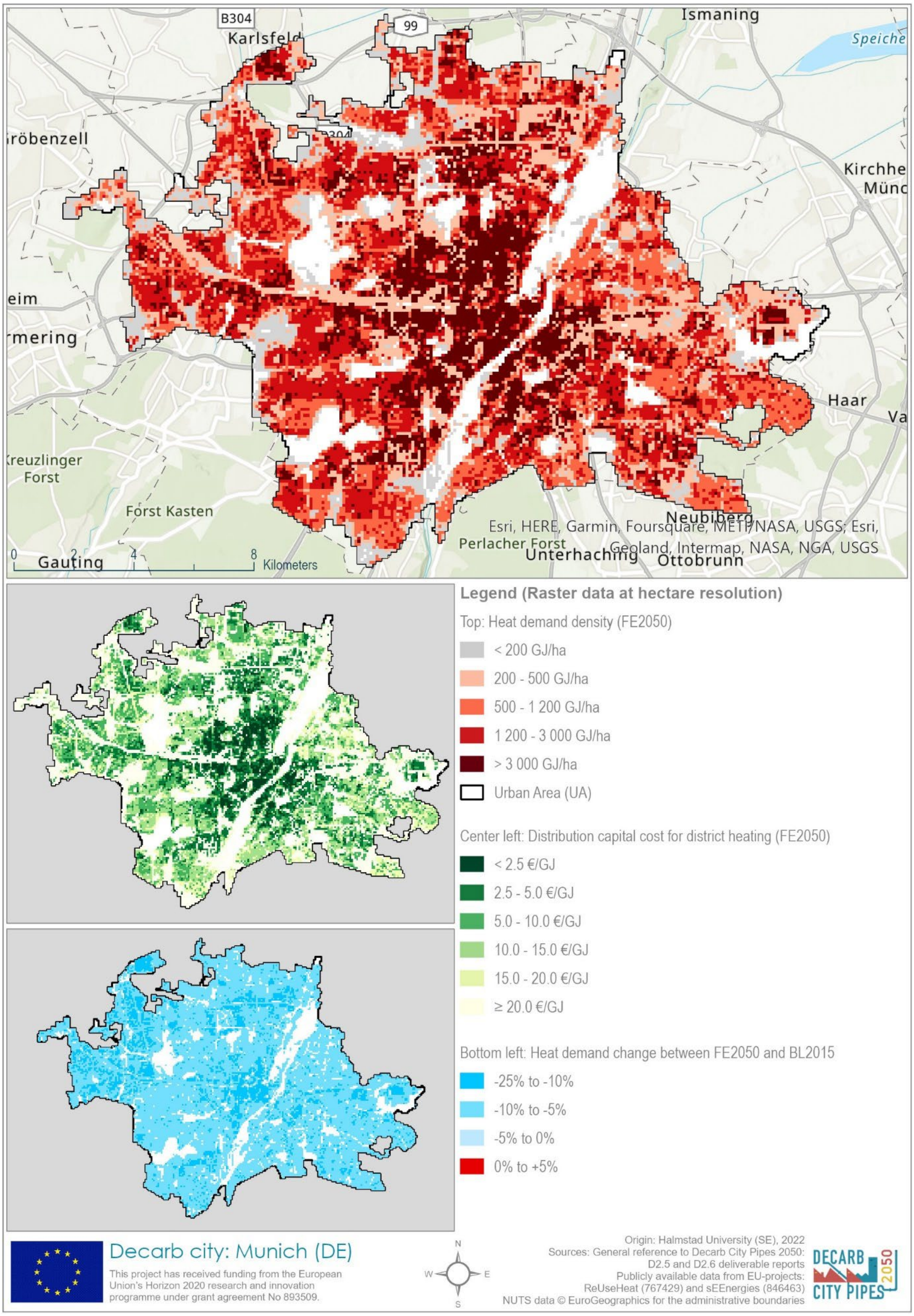


Figure 36. Munich map overview 3: heat demand density in 2050 (Frozen efficiency), distribution capital cost for district heating in 2050 (frozen efficiency), and relative heat demand change between frozen efficiency 2050 and baseline 2015. Sources: [27, 46, 50].

8.1.5. Rotterdam

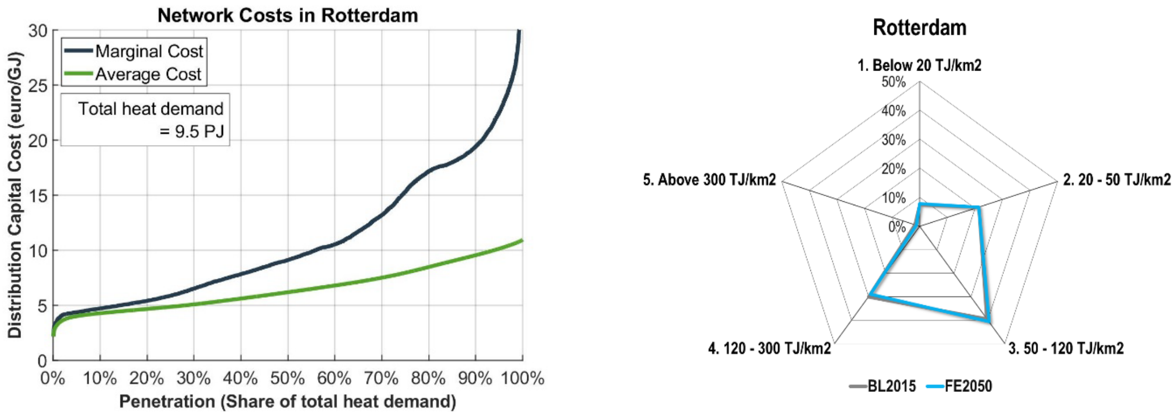


FIGURE 37. MARGINAL AND AVERAGE DISTRIBUTION CAPITAL COST LEVELS AND THE CORRESPONDING DISTRICT HEAT MARKET SHARES IN ROTTERDAM FOR FE2050 [€/GJ] (LEFT). COST LEVELS REFLECT COSTS FOR BOTH DISTRIBUTION AND SERVICE PIPES. AT RIGHT, RADAR DIAGRAM WITH RELATIVE SHARES INDICATING THE DISTRIBUTION OF TOTAL CITY HEAT DEMAND BY FIVE HEAT DEMAND DENSITY CLASSES (CURRENT YEAR INCLUDED FOR REFERENCE (BL2015)).

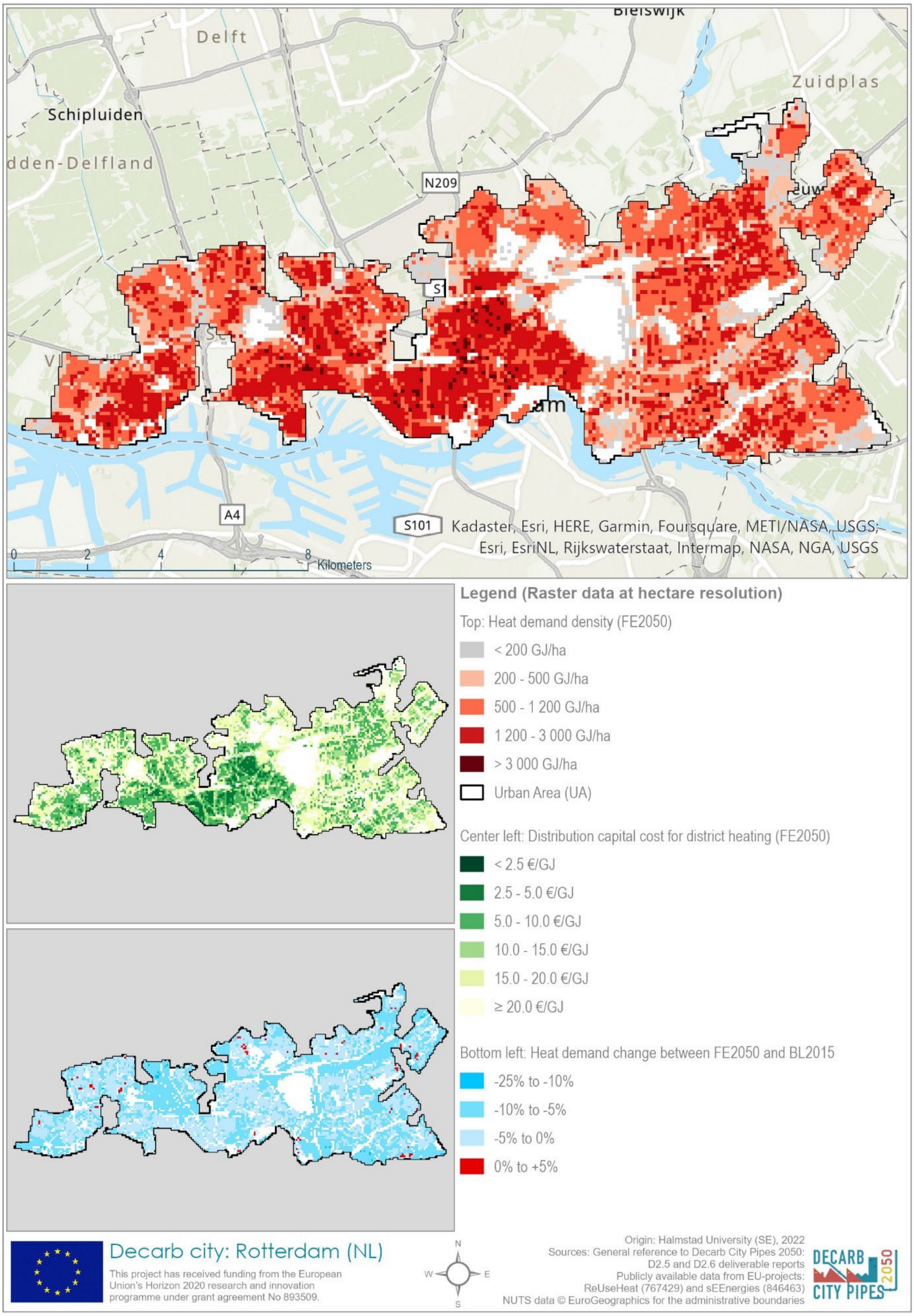
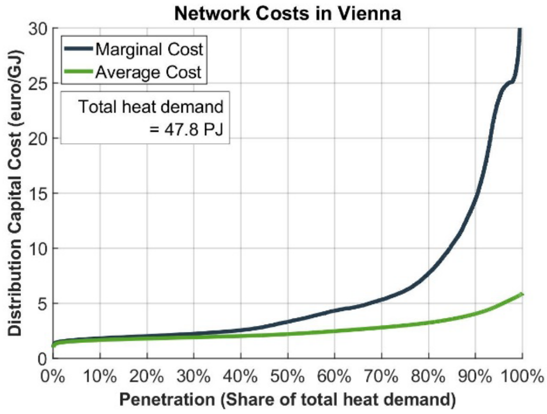


Figure 38. Rotterdam map overview 3: heat demand density in 2050 (Frozen efficiency), distribution capital cost for district heating in 2050 (frozen efficiency), and relative heat demand change between frozen efficiency 2050 and baseline 2015. Sources: [27, 46, 50]. Limitation note: Urban areas south of the Nieuwe Maas channel not included in the analysis.

8.1.6. Vienna



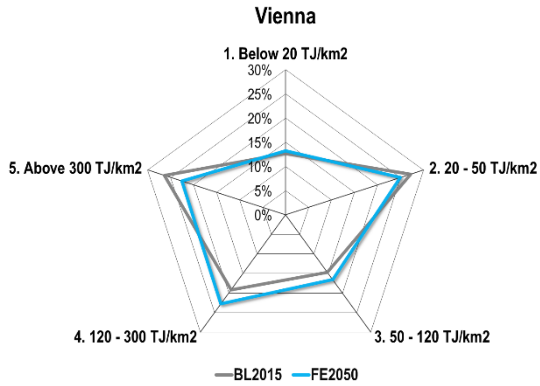


FIGURE 39. MARGINAL AND AVERAGE DISTRIBUTION CAPITAL COST LEVELS AND THE CORRESPONDING DISTRICT HEAT MARKET SHARES IN VIENNA FOR FE2050 [€/GJ] (LEFT). COST LEVELS REFLECT COSTS FOR BOTH DISTRIBUTION AND SERVICE PIPES. AT RIGHT, RADAR DIAGRAM WITH RELATIVE SHARES INDICATING THE DISTRIBUTION OF TOTAL CITY HEAT DEMAND BY FIVE HEAT DEMAND DENSITY CLASSES (CURRENT YEAR INCLUDED FOR REFERENCE (BL2015)).

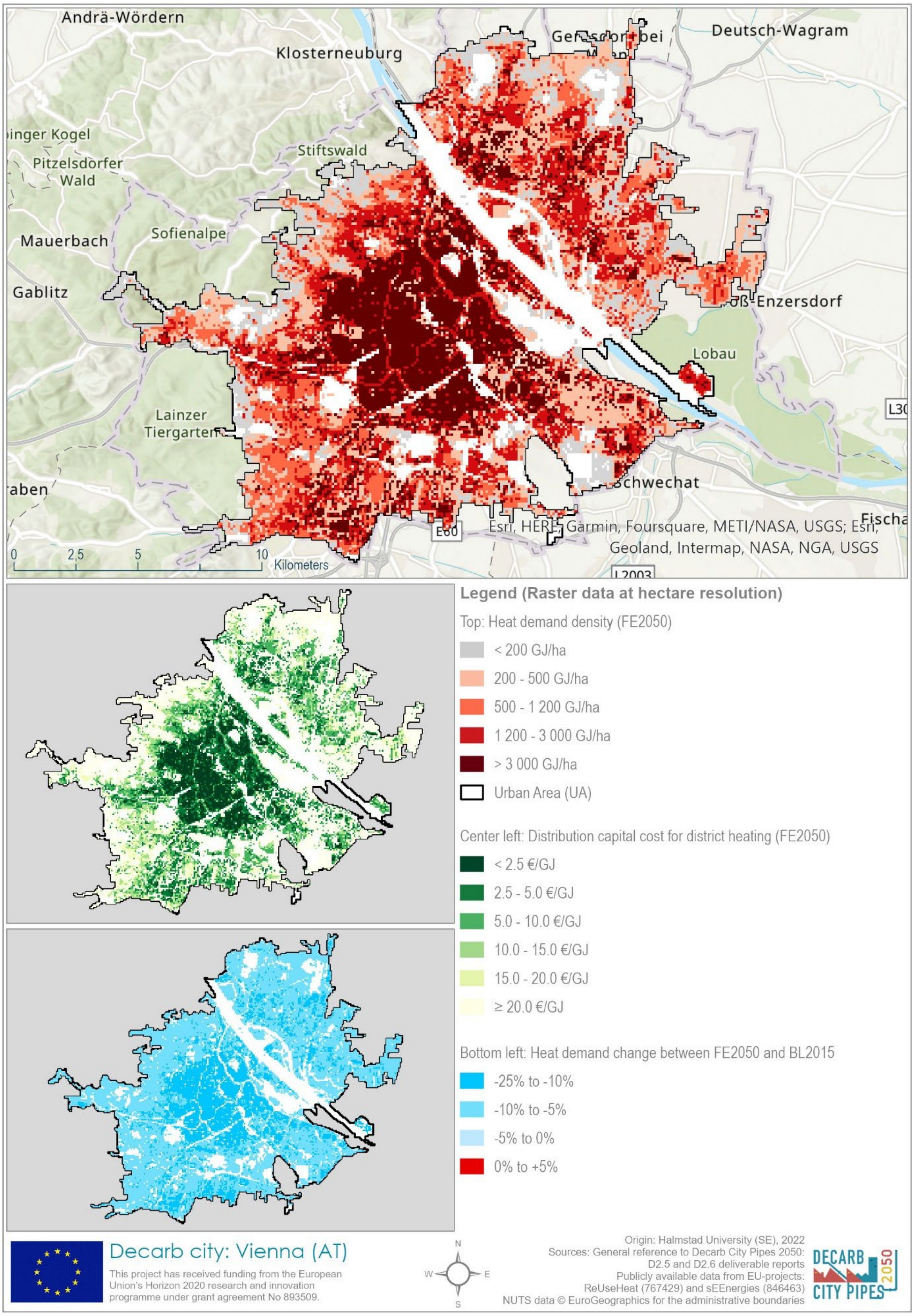


FIGURE 40. VIENNA MAP OVERVIEW 3: HEAT DEMAND DENSITY IN 2050 (FROZEN EFFICIENCY), DISTRIBUTION CAPITAL COST FOR DISTRICT HEATING IN 2050 (FROZEN EFFICIENCY), AND RELATIVE HEAT DEMAND CHANGE BETWEEN FROZEN EFFICIENCY 2050 AND BASELINE 2015. SOURCES: [27, 46, 50].

8.1.7. Winterthur

Neither distribution capital cost levels nor heat demand by five heat demand density classes were calculated for the city of Winterthur.

8.2. Intermediate TOPSIS results for ranking cities

Table 21. Weighted normalized matrix of the decarbonisation problem

Criteria	City population	Heating index	Heat Demand Density	Individual energy efficiency	Structural energy efficiency	Dependency on fossil fuels	Potential for renewable sources	Potential for waste heat	Development of the built environment	Coverage of district heating
Bilbao	-0,012	0,010	0,040	0,008	0,124	0,048	0,026	0,022	0,011	0,000
Bratislava	-0,012	0,014	0,039	0,031	0,067	0,016	0,032	0,012	0,012	0,132
Dublin	-0,001	0,014	0,018	0,064	0,032	0,048	0,011	0,022	0,020	0,000
Munich	0,010	0,015	0,044	0,032	0,093	0,027	0,083	0,023	0,004	0,056
Rotterdam	-0,006	0,014	0,029	0,024	0,059	0,039	0,038	0,101	0,016	0,034
Vienna	0,009	0,014	0,043	0,024	0,115	0,025	0,107	0,038	0,023	0,073

Table 22. The imaginary ideal and anti-ideal solutions of the decarbonisation problem

Criterion	City population	Heating index	Heat Demand Density	Individual energy efficiency	Structural energy efficiency	Dependency on fossil fuels	Potential for renewable sources	Potential for waste heat	Development of the built environment	Coverage of district heating
Ideal solution	-0,012	0,010	0,044	0,064	0,124	0,016	0,107	0,101	0,004	0,132
Anti-Ideal solution	0,010	0,015	0,018	0,008	0,032	0,048	0,011	0,012	0,023	0,000

8.3. Recommendations for 2050

First of all, cities´ supplies and demands of heat and cold need to be planned properly in order to achieve decarbonisation of current systems and to actually transition towards a fully fossil-free future H/C sector in the EU. This is not to say that city developments have not been planned in an organised manner in the past, but to emphasise that future planning activities need to be not only more extensive, but also more locally oriented while still keeping the bigger picture, the greater system, in view. This in turn means that planning activities themselves need to be facilitated by appropriate governmental structures and established so as to enjoy solid support, agreement, and adherence by local communities.

Secondly, decarbonisation of heating and cooling infrastructures requires funding in order to provide necessary investments in new systems as well as to compensate for the replacement and perhaps premature decommission of old ones. High upfront costs, long payback times, long life-cycles, stranded assets, not to mention unpredictable operational costs for energy and materials, require robust financial strategies and long-term programs if not to collapse half-way. In this respect, it is recommendable already at the outset to make clear also the difference between cost efficiency and energy efficiency, which not necessarily is the same, and the fact that without will and capacity to invest, there will likely be very little transition taking place.

Thirdly, there is a social influence and impact to consider, where social challenges and opportunities associated with a transition of current H/C supplies and demands also need to be understood and accommodated. A clear recommendation for cities initiating this kind of profound transition processes is to operate by inclusive strategies, to be transparent (with plans, data, costs etc.), to be clear and consistent, to communicate, to make sure that people are able and willing to join and support the process and, in the end, to foster public support by working together with stakeholders (utilities, industry, grid owners, other cities perhaps).

Fourthly, the process should incorporate an integrated and systemic approach which is capable of withstanding and deal with changes along the way. One important element of such approaches are sensitivity analyses, at the outset but also continuously updated, to ensure and improve the reliability and resilience of the process. Key dimensions to monitor and maintain under close watch include for example the continued affordability and sustainability of the original plan. Another element to consider is that of energy system modelling, by which is meant here the optimal combination of different measures, technologies, and infrastructures, where it is recommendable to realise that a short-term optima not necessarily is equal to a long-term one.

8.3.1. H/C plan: Cities' H/C supplies and demands in 2050

This subsection presents and discusses some recommendation which refers more explicitly to heat and cooling sector supplies and demands to be expected for cities in 2050. Such supplies and demands, and the corresponding barriers and opportunities associated with their utilisation and management, lies at the heart of any prospect to decarbonise city pipes. The presentation is general so that the recommendations may be relevant for any city and not only for the seven DCP2050 project cities.

- ***Energy supplies***

A fundamental first recommendation regarding energy supplies is not to confuse fuel sources with technologies and infrastructures. The typical example is when a city reports on its energy supply by stating “Natural gas 65%, Heat Pumps 20%, and District heating 15%”. This kind of presentation fails not only to provide the necessary data in order to fully characterise the actual energy supply, but it also reveals a lack of understanding of the system itself. Natural gas is a fuel, a heat pump is a technology which utilises electricity for its operation (in this example), and district heating is an infrastructure (which in fact can utilise both natural gas and electricity in its central supply).

Since many cities in Europe today, several of the DCP2050 project cities included, depend largely on natural gas for their energy supplies to the H/C sector, it is a quite natural reaction to look for an alternative in gaseous form. During the lapse of the DCP2050 project, that is during the last couple of years, there has been much interest, controversy, and debate, regarding the possible use of hydrogen instead. A second supply-related recommendation may thus be the apparent consensus reached on this point by more recent studies, for example Korberg et al. [70], who conclude that the use of hydrogen for low-temperature heating applications in the built environment most likely will be associated with high costs and low efficiencies, while being more suitable as e-fuel feedstock rather than direct end-fuel in hard-to-abate industrial applications.

Electrified energy supplies to the H/C sector, mainly by the use of compressor heat pumps, are esteemed as a main supply technology both for individual and central future applications. Depending of course on the nature and capacity of future renewable power generation, electrified energy supplies may further facilitate higher integration between different energy system sectors (power, gas, and thermal), which implies attention to systemic effects by its increased use. Hybrid solutions, additionally, for example with a combination of heat pumps and peak gas boilers, may provide intermediate routes towards full decarbonisation, but with apparent risks of technology lock-in effects.

An important recommendation in the context of such hybrid solutions, as well as in general, would be to consider, once again, the geography of the area and the prevailing supply systems. While typical low-density areas with limited possibilities for network heat distribution may benefit from such solutions during transitional phases towards full decarbonisation, other areas, such as current and future district heating areas, may be hampered by it. In this respect, the spatial dimension of energy supplies, which should be evident from the above, is so important that it deserves specific mention here. By apt planning and consideration, useful waste heat activities of the future, such as data centres and exothermic industrial processes, could deliberately be located much closer to settlement areas in order to facilitate synergetic excess heat recoveries.

- ***Energy demands***

Regarding future energy demands, which basically are subject to developments in the built environment (renovation and demolition rates, floor areas, building standards etc.), in demographics and populations (number of people, population densities etc.), as well as external developments such as ambient temperature increases, politically formulated targets, taxation regimes etc., it is very difficult to predict their volumes and locations in 2050. For guidance, perhaps it will suffice here to reference one of the most used sources today, the PRIMES model projections for the EU in 2050 (by Capros et al. [60, 61]), as a standard recommendation regarding this kind of information.

As for energy supplies, it is further recommended to keep particular focus on the likely and expected spatial distribution of future energy demands, which geographical distribution is indicative of different decarbonisation design approaches and measures, and which, for their efficient provision, leads the way into dedicated strategic heat planning.

8.3.2. Strategic heat planning

In the recognition of the complexity that characterises future planning in general, and that of future heat planning in particular, Djørup et al. [23] presented in 2019 a handbook for strategic heat planning based on experiences from the Hotmaps project [30]. According to the handbook, strategic heat planning is by nature interdisciplinary and often involves a variety of actors and stakeholders such as public authorities, private companies, energy utilities, consumers, as well as other institutions and organisations.

The handbook introduces a three-phase framework for strategic heat planning, consisting of clearly listed sub-items, as presented in Table 23. The first phase is fairly analogous to the H/C outlooks and heat plans prepared by the DCP2050 project city partners, while the second (Evaluate existing framework conditions and identify key stakeholders) and third (Make an implementation plan), phases relate to the transitional roadmaps.

TABLE 23. THREE-PHASE FRAMEWORK FOR CARRYING OUT STRATEGIC HEAT PLANNING ACTIVITIES (FREE ELABORATION FROM CONCEPTUAL FRAMEWORK PRESENTED IN [23])

Phase 1	**Construct technical scenarios for a strategic heat supply (H/C outlooks & Heat plans)**
(1) Quantify heat demand	
(2) Assess and quantify the availability of heat resources in the area	
(3) Assess and quantify the potential for heat savings in buildings	
(4) Identify a balance between investments in heat supply and heat savings	
(5) Align with national/regional/local energy plans	
(6) Develop technical alternatives and scenarios for a strategic heat supply plan	
(7) Repeat Steps 4-5-6 in search for the best solution	
Phase 2	**Evaluate existing framework conditions and identify key stakeholders (Transition roadmaps)**
* Identify economic and political barriers	
* Identify economic and political opportunities	
* Identify key stakeholders (if not already done in the preparation phase)	
* Develop ownership and business models that align with strategic objectives	
Phase 3	**Make an implementation plan (Transition roadmaps)**
* Identify which framework conditions that can be changed by the relevant planning authority	
* Design new regulation and framework conditions	
* Identify opportunities to involve stakeholders that can play a constructive role in realising the heat plan	
* Design/redesign organisations to deal with planning and coordination challenges	

- ***From technical scenarios to implementation plans***

Firstly, it is recommended before starting the process of actual strategic heat planning to establish an overview representation and understanding of the current situation (preparation phase). What are the unique problems and challenges in the particular case? What is the current heat supply and what changes have been made historically to the system? What have been the driving incentives of previous changes and what are the likely drivers of changes to come? Who have been involved before and who could be expected to contribute up ahead?

By answering this kind of questions, a first order understanding of the current situation can be reached upon which basis a set of concrete objectives could be formulated which describes the expectations of the future heating and cooling system at hand and the transformation process to initiate. As for the DCP2050 project cities, all are already beyond this preliminary stage and have moved on into one of the three phases outlined in Table 23, where the seven sub-item steps of Phase 1 all relate to the construction of technical scenarios for a strategic heat supply.

Secondly, the first three sub-item steps of Phase 1 are those that most often are associated with dedicated "heat mapping", i.e. the (1) quantification of building heat (and cold) demands (as well as the geographical distribution of these demands), the (2) assessment and quantification of locally available heat (and cold) resources (as well as their geographical locations), and the (3) the assessment and quantification of potential heat savings in buildings. In the latter case, requirements in continuously updated national-level building standards may provide data and indications regarding this potential, but it also relates to demolition, refurbishment, urbanisation, and even densification, rates, all of which are likely parameters to consider in this step. As such, sub-item steps 1 to 3 under Phase 1 represent themselves quite comprehensive undertakings, which to a considerable degree usually also consist of assembling statistics and various data for the different quantifications that cannot be omitted if to properly be able to continue with sub-item steps 4 to 6.

Thirdly, by the fourth sub-item step under Phase 1, that is by (4) identify a balance between investments in heat supplies and heat savings, the strategic heat planning initiative now comes to include also dedicated energy system modelling on top of the geographical mapping and statistical analyses of the previous steps. Where is the cost-optimum between investments in heat supply and those in heat savings? The answer to this question, which may be different depending on the unique local conditions at any given locations, will eventually have to relate back to the principal concepts of structural[22] versus individual[23] energy efficiency measures[24], both of which are included among the ten structuring criteria elaborated in the coherent methodological framework.

Fourthly, the fifth sub-item step under Phase 1, that is (5) align with national/regional/local energy plans, introduces the next field of action to the strategic heat planning framework. The alignment of energy planning from the local, to the regional, and eventually to the national level, and vice versa, represents an important dimension distinct from the technical and economic considerations of the previous steps. With respect to heating and cooling, there are synergies to be harvested, or lost, if appropriate overview perspectives can, or cannot, be established among local and regional stakeholders. Moreover, this item may very well be understood in extension as the development of formal requirement for strategic heat planning routines within municipal government in the EU. The south-western German state

[22] Technical/systemic measure reducing primary energy demands by increased recovery efficiencies in central or local conversion while maintaining equivalent end use levels.

[23] Technical/systemic measure reducing primary energy demands by absolute decreases of end use energy demands and/or by increased conversion efficiencies in central or local conversion while reducing equivalent end use levels.

[24] Any reduction of the primary energy demand in an energy system must be conceived as an energy efficiency measure. However, whereas this efficiency gain can be obtained by central solutions, i.e. by supply side investments in e.g. district heating systems and excess heat recovery technologies (increased recovery efficiencies), it may likewise be obtained by individual solutions, i.e. demand side investments in e.g. heat saving measures in buildings (end-use demand reductions) and more efficient end-use applications (increased conversion efficiencies). Since these different measures are associated with different costs (at different conditions), a cost-optimum between them should be identified for each given case. See further also reference [14].

of Baden-Württemberg recently introduced compulsory municipal heat planning for cities and larger towns [25], which might serve here as an example of this plausible development.

Fifthly, the sixth sub-item step of Phase 1 in Table 23, that is (6) the development of technical alternatives and scenarios for a strategic heat supply plan, may be viewed as the orderly assembly of all the data gathered in the previous steps and subjecting this to energy system modelling and sensitivity analyses. The analysis should relate back to the strategic objectives first identified in the preparation phase and, by use typically of a baseline scenario, illustrate the different alternatives by comparative analysis. In the end, this should facilitate a decision where the most feasible technical scenario is agreed upon.

As for the two remaining phases outlined in Table 23, Phase 2 focusses on the evaluation of existing framework conditions and the identification of key stakeholder while Phase 3 stipulates the making of an implementation plan. Under each of these headings, four sub-item steps are presented: addressing economic and political concerns on the one hand, and regulatory, stakeholder, and coordination challenges on the other.

There are several other representative examples of how strategic heat planning can be arranged and organised, which might be mentioned here as useful references, however, the basic ideas in most of these different accounts are quite similar. In a recently published report from IRENA [71], the same key elements as in the three-phase framework presented in Table 23 are present, although first emphasis is given here on the identification of main stakeholders to engage in the process and on the political drivers and strategic objectives upon which they should act. Apart from the standard construction of technical scenarios (mapping of demands and assets), the report further stresses the importance of aligning and adapting national level policies and regulations so as to properly meet and live up to local level requirements. The integration of renewable energy sources should be conceived in view of the entire energy system, which implies governance activities at all levels.

- ***Long-term goals and long-term strategies***

Another well-conceived and pedagogical account is the recent work of Kicherer et al. [24], in which a roadmap for the transition of the district heating system in the city Hamburg, Germany, is presented. Given that the focus is limited to an existing district heating system, the suggested procedure is an elaboration of the three-phase framework of Djørup et al. in [23]. Accordingly, three main elements constitute the core structure also here, but the strategic heat planning framework is in this case arranged according to the following steps:

- (1) Survey of current heat supply
    - Including aspects such as political boundary conditions, heat supplies and demands, and an analysis of the current system
- (2) Determination of long-term goals and demands
    - Including political climate protection goals, economic goals, social goals, and future heat demands
- (3) Development of a long-term strategy
    - Including an analysis of renewable heat potentials, an assessment of heat generators, and the development of a scenario for 2050, as well as the formulation of a long-term strategy from the current year to this future year (2020 to 2050).

In conclusion, the study suggests that “an institutionalized process for municipal heat planning can support a comprehensive transformation of a city’s heating structure and ensure a continuous and flexible adaptation of the heating strategy” (on page 10 in [24]), a quote which underpins the above-mentioned notion recently adopted in Baden-Württemberg concerning mandatory municipal heat planning.

Regarding other source references for literature on strategic heat planning, there is an increasing flora of reports and papers in this field today. One recommendable report, which also should be useful with practical tips and links for local working groups around Europe, is a dedicated guide to heat mapping published within the context of the HeatNet NWE project a few years ago [72]. This report maintains a stricter focus on the use of GIS in the concrete mapping of heat and cold demands and resources under various context, by various approaches, and by various data access conditions (essentially corresponding to Phase 1 in the three-phase framework of Djørup et al. presented in Table 23 above). Notably, the report includes a comprehensive table of useful links to various data and information sources open to the public, sources which by their availability, as discussed further in the next section, by themselves represent H/C sector transition measures.

8.3.3. H/C sector transition measures

This final subsection presents in brief an additional set of recommendations expressed in relation to some concrete thematical transition measures for the heating and cooling sector, namely: Data and information, energy zoning, densification, mandatory connection, regional energy planning mandate, funding and ownership structures, and regulatory simplicity.

- ***Data and information***

Regarding data, don´t reinvent the wheel unless this is of particular interest to you. There is by now quite a lot of publicly available data on city level, both locally generated, so-called, bottom-up data, as well as so-called top-down modelled continental-level data. Use it! As a direct guidance, here are references and links to some relevant European data and information sources (of course, there are many more):

- *The Pan-European Thermal Atlas [33]*
  - https://www.seenergies.eu/peta5/
- *The sEEnergies Open Data Hub [73]*
  - https://s-eenergies-open-data-euf.hub.arcgis.com/
- *Hotmaps - The open source mapping and planning tool for heating and cooling [30]*
  - https://gitlab.com/hotmaps?page=1
- *The European Waste Heat Map (ReUseHeat [31])*
  - https://tinyurl.com/2wvh7ud7
- *Copernicus [74]*
  - https://land.copernicus.eu/pan-european/corine-land-cover
- *Eurostat – Your key to European Statistics [75]*
  - https://ec.europa.eu/eurostat/web/gisco/overview

Noteworthy, local mapping, generating unique bottom-up data, at city level is the recommended preference for local studies, while continental top-down data may be used as indicative first order assessments where local data is not available. For further references regarding data access, data quality, and data management, see also the earlier WP2 output on the subject (the D2.4 report [56]).

- ***Energy zoning***

The central idea of energy zoning is, by way of detailed strategic planning for a cities' energy supply, the designation and allocation of certain solutions (or, as here, decarbonisation design approaches) to certain areas and city districts within the city, and not so to others. Hereby, energy zoning relates primarily to the sub-city level, as exemplified for the city of Dublin above in subsection 4.2, where its main benefit is the obtainment of high connection rates to whatever infrastructure that has been determined as that preferred in the zone.

- ***Densification***

Densification has been widely recognized as a strategy to transit toward sustainability in urban residential and industrial areas. Among others, energy-related issues are one of the key aspects aimed to be addressed by this paradigm. As considered and discussed in relation to the ten structuring criteria in the framework approach, higher demand density is an index economically and environmentally supportive of the development of district heating and cooling systems. In scattered population regions, investing in heating and cooling networks would not be justifiable, why measures are forced to shift to less structurally energy efficiency solutions, even in some cases, to non-renewable and less sustainable solutions.

However, the advantages of densification are not limited to heating and cooling but rather benefits the whole energy sector. It can reduce per capita energy consumption by, for example, giving rise to lower transportation demand, higher service rates, and fewer relative numbers of required infrastructures, facilities, and plants.

Densification has been an ongoing phenomenon in recent decades as the number of rural inhabitants has been decreasing in favour of city dwellers, and this trend is expected to continue in the upcoming years (At least up to 2050 for the EU, according to the United Nations World Urbanization Prospects [76]). However, acceleration of this transformation in a more purposeful, systematic fashion is needed. On this path, of course, it is of crucial importance to take local capacities, social, and well-being dimensions into consideration.

- ***Mandatory connection***

The word "mandatory" has for many a certain unpleasant ring to it, but when it comes to heating and cooling, and in particular to the decarbonisation of these sectors, which itself will requires change and transition, it is perhaps only to be realistic to speak such words out loud. The European Commission, for example, proposed in the recast Energy Efficiency Directive to make heating and cooling plans compulsory for municipalities above a threshold of 50,000 people. Although there are some controversies about the threshold value, there appears to reign an overall agreement on the obligation itself.

EU Member States have also been required to introduce energy efficiency obligation schemes. Various, sometimes conflicting interests among different stockholders and actors engaged in heating and cooling systems on the one hand, and the necessity of moving toward green, efficient energy systems on the other hand, demand mandatory concrete goals, plans, or policies by which all the actions and operational programs are focused on a common direction. The mandate is supposed to impose requirements on gradually shifting away from fossil fuels towards renewable and alternative sources, as well as reusing waste heat. Here is where local, regional, national, and international, support should come to assist those parties who are in financial and technical troubles on the way to achieving the targets.

In terms of district heating systems, local communities in Europe who struggle with poor economy in existing and planned heat distribution networks, when due to low connections rates, would indeed be helped in their H/C decarbonisation efforts if able to increase future connection rates by means of, for example, energy zoning and mandatory connections.

- ***Regional energy planning mandate***

Given the local context of thermal supplies and demands, as well as the well-recognised fact that exploitation of locally available synergies, for example, by means of industrial waste heat recoveries, requires local knowledge, local stakeholder collaborations, local agreements etc., a general recommendation for regional energy planning mandates is considered appropriate in this context. Add to this, as explicitly shown and illustrated in this report, the spatial relevance and impact on the design of urban energy system, this recommendation would be further emphasised.

- ***Funding and ownership structures***

Without penetrating too far into the topic here, may it perhaps be relevant to ask today, in view of the severe challenges cities are faced with, whether standard market-economy funding and ownership principles are sufficient to incentivise and facilitate the long-term and large-scale investments needed to meet these challenges? Put differently, are this type of commonwealth investments not beyond the capacity of ordinary utility business cases?

- ***Regulatory simplicity***

No or very little progress is likely to be possible without clear goals, which indeed motivates the creation and maintenance of quantified targets to strife for. However, the final recommendation in this work is to keep the rules which regulate the actions allowed to reach such targets as simple as possible. You cannot expect the ordinary citizen to comply with laws which is incomprehensible due to complexity and excessive volume.

DECARB CITY PIPES 2050

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 893509