Draft recommendations for H/C outlook 2050

Deliverable D2.2

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Finalised: June 2021

PROJECT INFORMATION

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

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Executive summary

This report presents draft recommendations in response to the first initiatives and insights among six local working groups (LWG's) in six European cities 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), all of which are partners in the EU Horizon 2020 project *Decarb City Pipes 2050 - Transition roadmaps to energy efficient, zero-carbon urban heating and cooling*.

The presented draft recommendations are thought to be supportive and directional for the partner cities, but also to provide insights, ideas, and suggestions of general interest. The report consists of an introductory section which outlines a framework for strategic heat planning and discusses a number of thematical and key concepts, followed by six city-specific sections with descriptions of the current situation and the first future heating and cooling outlooks for each city respectively. The report also includes two in-depth subsections, the first of which presents a dedicated feasibility study for district heating in the city of Bilbao, the second of which answers questions relating to extensions of current district heating systems and pricing of district heat, raised by the city of Vienna.

If condensed and sorted by main topics, the draft recommendations presented in this report are to investigate the feasibility of district heating in the city if it doesn't already exist, and, if it exists, investigate how to densify its uptake, how to increase its current connection rates, and how to decarbonise its supply by integration of locally available renewable and excess heat resources. For the latter, approaches whereby to obtain lower network distribution temperatures is seen as a priority. In general, evaluate and put in effect programs by which the current building stock is retrofitted and refurbished so as to obtain reduced heat demands for space heating and domestic hot water preparation in view of a cost-optimum relative investments in heat supply. Maintain a regional perspective and a regional level organisation and coordination of your strategic heat planning initiative, and, as far as possible. work together because despite whatever other resources you may have at hand, the dedication, effort, and camaraderie of your colleagues is without doubt the most valuable resource of all.

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) and domestic hot water preparation (DHW) 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 H/C supply mix during the last twenty years (from 10.4% in 2004 to 20.5% 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 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. For these reasons foremost, the decarbonisation of the heating and cooling sector in Europe represents an opportunity and a key 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 (project No. 893509, full title: *Decarb City Pipes 2050 - Transition roadmaps to energy efficient, zero-carbon urban heating and cooling*). The 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 accept 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.

This report is the second out of four accounts in Work Package 2 (WP2) of the project with explicit focus on the H/C outlooks that are being prepared and elaborated by the LWG's as steeping stones towards the final Transition Roadmaps 2050. The first account was the initial 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 is this report, *Draft recommendations for H/C outlook 2050* (Deliverable 2.2), which serves the purpose of providing an overview, a resumé, answers to questions raised by LWG's so far, and some first responses (draft recommendations) to the roughly sketched *H/C supply outlooks 2050*, which each LWG reached agreement upon under Milestone 2 (MS2)[1] in project month 11 (May 2021). These two first accounts are both associated with dissemination level confidential and will thus be available only for members of the consortium (including the Commission Services). The third account, *H/C outlook 2050 of cities with cross-city synthesis* (Deliverable 2.6), and the fourth, *Recommendations for cities' H/C supplies & demands in 2050* (Deliverable 2.7), are both public and scheduled for project month 26 (August 2022) and project month 27 (September 2022) respectively.

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

1.1. Decarbonisation of heating and cooling

It is fair to say that heating and cooling technologies and infrastructures, and the complexity by which these are associated to the energy system in which they are constituent parts, has been a neglected and principally ignored area of understanding and interest for the general EU citizen for as long as anyone can remember. While having been relieved of such challenging considerations for generations, as long as the alarms were all still silent, the young Europeans of today and tomorrow, unlike their parents and forefathers, have had to react instinctively and become rapidly aware of these systems and interrelations by a rate never seen before. The European community emerges as global forerunner in terms of environmental and ecological insight and has, by an impressive production of legislative acts and reforms within the fields of energy efficiency [3, 4], renewable energy [5], and future green and circular economies [6-8], during the last decades, managed to build a solid foundation in support of societal change and transformation towards greener economies and, in particular, towards more sustainable provisions of heating and cooling services.

In the face of challenges at such grand scales, that is the fundamental transition of our own created societal infrastructures and systems for energy provision, which we have created in our own image as a result of our state and the conditions surrounding us here on the planet, we have to realise that the solutions needed most likely are not be found in our old toolboxes. On the contrary, the decarbonisation of H/C systems around Europe will require new concepts, new ideas, new thinking; “out of the box”, because the *Path Dependency*, that is the “business as usual” and the “standard procedures”, of our ways, by which we formed the existing system, evidently is not sufficient for its transformation into something else and therefore has to be broken.

As the LWG’s now take on these challenges to prepare their Transition Roadmaps 2050, there are several other key concepts, other than Path Dependency, that have relevance to their work. Directly related here is also the concepts of *Technology Lock-in*, which relates to the fact that investments in energy infrastructures most often have long time horizons and that there is always a risk for lock-in effects in systems dominated by one single technology solution. Another important concept is that of *Energy System Integration*, which points to the many times hard-to-see systemic benefits obtainable with higher degree of interconnectivity between the main energy system sectors of power, gas, and thermal networks. In the heating sector in particular, district heating (DH) systems equipped with cogeneration units, Power-to-Heat (P2H) capacities, and thermal storages, if coupled with the power sector, are capable of providing systemic benefits by both producing and consuming electricity.

Another key concept to keep in mind is the *Population Development Trend*, in this case especially for the year 2050. In this context, not only the total number should be of interest but in particular the expected *Urbanisation Rate* in the future. Due to several reasons, such as building renovation rates and improved building standards, specific building heat demands (heat demand by square meter floor area) are already decreasing and are expected to continue to do so. However, the spatial concentration of specific building heat demands, that is the *Heat Demand Density*, is the actual measure by which to appreciate and evaluate techno-economic conditions for different heat supply technologies. This key concept, Heat Demand Density, is central not just for anyone who sets out to assess opportunities for various heat supply technologies, but is so also in this report. For each of the six presented cities, a dedicated overview map of heat demand density is presented.

Last, but not least, when discussing the decarbonisation of heating and cooling, the key concept, which we may label *Local Conditions*, cannot go unnoticed. The emphasis on this key concept was one of the fundamental pillars upon which the original Heat Roadmap Europe concept was based, as it was first introduced in 2012 [9, 10]. The recognition at the heart of the new methodological approach put forward by the Heat Roadmap Europe consortia, which, in short, was to combine high-resolution spatial mapping and energy system modelling to better understand opportunities for increased energy efficiency and use of renewable energy resources, was the fact that thermal infrastructures – different from both electrical and gas infrastructures – are strictly local.

The local dimension constitutes the setting by which locally available heat and cold resources may be exploited to supply locally available heat and cold demands – in the envisioned decarbonised heating and cooling systems of the future! It should be a no-longer appropriate “standard procedure” of the past to send energy over and across the continent in the form of electricity and gas for use in individual heating applications such as apartment boilers and resistive heaters. Electricity and gas grids are of course essential infrastructures in any energy system, past, present, or future, but they would not necessarily have to be the main providers of energy for the low-temperature heat demands in focus here. Instead, to keep our homes, our work places, our schools, and public buildings, warm and liveable, we should strive to make full use of all those locally available heat resources that today and hitherto have been allowed to just dissipate into the ambient unused. For this end, however, the local dimension needs to also include local district energy infrastructures, such as district heating systems, without which there are no recovery infrastructures by which to distribute and reuse locally available heat resources.

The necessity of the local dimension is in this sense the main driver for the anticipated structure and appropriate design of this project. After a decade of pioneering continental-level EU-projects which have investigated local conditions basically from top-down perspectives, such as (the above mentioned) Heat Roadmap Europe project [9], the Hotmaps project [11], the ReUseHeat project [12], the sEEnergies project [13], and several others, the natural next step is to go deeper and to perform strategic heat planning and geographical mapping of assets and demands at the local and regional scale. If this is true, Europe can expect to see hundreds, why not thousands, of highly detailed, locally scoped, heat maps becoming available on the Internet in the years to come. And this would be quite appropriate because the peculiar thing about local conditions, which, by the way, we shall have occasion to observe also in this report despite being limited here to only six European cities, are unique and special for each and every location not just in terms of physical and geographical contexts, but most often so also in view of cultural, demographical, organisational, and governmental dimensions.

During the year that has passed since the project started (on July 1, 2020), the LWG’s in the six studied cities have had initial meetings and engaged into discussions and activities towards the final Transition Roadmaps 2050, that will represent the results for their efforts in this project. As further presented under each city sections in this report, some topical challenges have drawn particular interest already, for example the issue of phasing-out natural gas as a dominant energy carrier and the prospects for deep geothermal energy in highly populated and dense urban areas, both of which represent real and pivotal issues to address for successful transitions. Anyone who seriously began investigating the possibilities and barriers associated with the challenge of decarbonising heating and cooling systems on a city-wide level, already knows that some kind of principal Code of Conduct, a manual if you like, is essential if not to get lost in the maze. This is where the key concept of *Strategic Heat Planning* comes in.

1.1.1. 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. [14] presented in 2019 a handbook for strategic heat planning based on experiences from the Hotmaps project. 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 representative three-phase framework for carrying out strategic heat planning, consisting of clearly listed sub-items, as presented in Table 1.

TABLE 1. THREE-PHASE FRAMEWORK FOR CARRYING OUT STRATEGIC HEAT PLANNING ACTIVITIES (FREE ELABORATION FROM CONCEPTUAL FRAMEWORK PRESENTED IN [14])

Phase 1 Construct technical scenarios for a strategic heat supply

- (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

- 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

- 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

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 your 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 six cities in the project, all are already beyond this preliminary stage and have moved on into one of the three phases outlined in Table 1, 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 we most often associate 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 of these, 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 consists of assembling statistics and various data for the different quantifications, but 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 nature of our strategic heat planning initiative has now come 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? Well, despite the answer to this question, which, once again, may be very different depending on the unique local conditions at any given locations, the relevance of the answer relates to the principal concepts of *Structural*[2] versus *Individual*[3] energy efficiency measures [15]. 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 savings 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), the sought cost-optimum needs to be identified for each given case and there is just no way around it. For reference on this particular issue, the authors are preparing yet another project deliverable in parallel to this report, where the cost-optimum between investments in heat supply and heat savings is discussed in more detail. The related deliverable is public, titled *Techno-economical possibilities and system correlations (with pros and cons for the participating cities as input to their local discussions)* (Deliverable 2.3), and is due by project month 12 (June 2021).

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 only, or not, appropriate overview perspectives can be established among local and regional stakeholders. The concept of *Industrial Symbiosis* may serve as a sufficient example of the kind of synergies possible to harvest by appropriate planning synchronisation, for the moment being. In essence, however, this item

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

[3] 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

may very well be understood in extension as the development of formal requirement for strategic heat planning routines in European municipal government. The south-western German state of Baden-Württemberg, as the first, recently introduced compulsory municipal heat planning for cities and larger towns, which might serve here as an example to prove the point [16].

Fifthly, the sixth sub-item step of Phase 1 in Table 1, that is (6) the development of technical alternatives and scenarios for a strategic heat supply plan, may be viewed as the assembly of all data and information gathered in the previous steps and submitting this modelling and sensitivity analysis. The analysis should relate back to the strategic objectives first identified in the preparation phase and, by use of typically 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 1, 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 (International Renewable Energy Agency) and Aalborg University in Denmark, titled *Integrating low-temperature renewables in district energy systems: Guidelines for policy makers* [17], we recognise the same key elements as in the three-phase framework presented in Table 1, 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.

Another well-conceived and pedagogical account is the recent work of Kicherer et al. [18], 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 [14]. Accordingly, three main elements constitute the core structure also here, but the strategic heat planning starts in this case with (1) the survey of current heat supply (including aspects such as political boundary conditions, heat supplies and demands, and an analysis of the current system). Secondly, (2) the determination of long-term goals and demands (including political climate protection goals, economic goals, social goals, and future heat demands). Thirdly, (3) the development of a long-term strategy (including the analysis of renewable heat potentials, the assessment of heat generators, 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, it is suggested 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”.

The above cited concluding remark from Kicherer et al. (on page 10 in [18]) brings about, again, the notion previously exemplified with the Baden-Württemberg case, where the bold step recently was taken at state level to simply make municipal heat planning mandatory. The word “mandatory” has a certain unpleasant ring to it, which most Europeans likely would agree to, but when it comes to heating and cooling, and in particular the decarbonisation of these sectors, which itself will require profound societal change and transition as we have seen, it is perhaps only to be realistic to speak such words out loud. The alternative, which we all know rather too well by now, is to let the market decide, meaning that each actor who is able to finance its own activity may go ahead and put into operation heating and cooling technologies and infrastructures without any consideration whatsoever of overarching strategic concerns and the harvesting of synergy benefits. Whatever way we choose, mandatory or at free will, local communities in Europe need to realise and integrate routines for strategic heat planning as a means by which to decarbonise their heating and cooling sectors.

In addition, and as further recommendable input to the six LWG’s in their ongoing work to create H/C outlooks and transition roadmaps for their respective cities, firstly, one more useful reference for strategic heat planning may be found in the *Guide to Heat Mapping* published within the context of the HeatNet NWE project a few years ago [19]. This report maintains a stricter focus on the use of Geographical Information Systems (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.). Notably, the report includes a comprehensive table of useful links to European and national level spatial data resources. Secondly, the following sub-sections presents and briefly discusses three additional thematical concepts under separate headings. These thematical concepts relate to some basic principles associated with energy systems and the supply and use of heat and cold in such systems, as well as to our understanding of technical and non-technical dimensions, and their interrelation, as a prerequisite for successful societal transition.

1.1.2. Central and individual solutions

The significance of central versus individual solutions is twofold in the context of this report. Firstly, the theme relates to energy efficiency measures, as briefly mentioned above, and secondly, this theme relates to the paramount quantity of heat demand density, both of which will be discussed further in the following.

As for the first theme, if viewed principally, energy efficiency gains in an energy system can consist of basically two different types of measures. On the one hand, supply side energy efficiency measures reduce the primary energy demand 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. The authors have previously analysed the EU energy system from such a perspective and introduced concepts, for example *Parallel and Serial Supply Structures*, *Excess Heat Recovery Rate*, *Excess Heat Utilisation Rate* etc., by which to express and quantify structural energy efficiency measures, see ref. [20]. Measures of this type will likely require investments in infrastructures, in district heating and cooling systems, in transmissions, distribution, and service pipes, in heat generation units, in heat exchangers, in building substations etc., and are often associated with relatively long economical life times and relatively high up-front investment costs. For the particular case of the city of Bilbao, we present in section 0 a dedicated feasibility study of a district heating system in this city, a section which is thought to be of general interest and value also for the other project cities.

On the other hand, demand side energy efficiency measures, or as they may also be labelled, individual energy efficiency measures, reduce the primary energy demand of the system by reducing the absolute magnitudes of final end-use demands in the system, i.e. by direct heat savings through improved insulation of building envelopes, by replacement of windows and other building components, and by use of *Best Available Technologies (BAT)* in end-use conversions, hereby exploiting higher conversion efficiencies in final consumption. Measures of this type will likely require investments in new building envelope components to foster heat savings, in new individual heat generation systems such as condensing boilers and heat pumps for more efficient local conversion, and in other technologies to improve end-use applications.

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) 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), the opposite is the case, i.e. the system itself remains inefficient but still manages to reduce its primary demands since final end-use demands have been minimised. A contextual consequence of this dynamic to keep in mind is therefore that – depending of 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 the main underlying rationale for always striving to identify the optimal balance between supply and demand side investments respectively, the purpose being of course to identify and organise the most appropriate system at lowest cost by avoiding sub-optimisations and technology lock-in effects.

Before approaching the second theme under this heading, that of heat demand density, the point should be expressively made that energy efficiency measures, preferably at this discussed optimum, must be, yes, mandatory in any serious strategic heat plan. In fact, energy efficiency, the reduction of primary energy demands in the local, regional, national, and eventually, in the continental energy system, as a result of central and individual solution together, cannot be omitted if to arrive successfully at a future decarbonised heating and cooling sector. This means, among other things, that as specific building heat demands (energy unit per floor area) are being reduced as a result of individual energy efficiency measures, the opportunities for structural energy efficiency measures, by means of recovery and reuse of various waste heat sources in district energy systems, are also being likewise reduced. Is it an unsolvable enigma? A Gordian Knot? The second theme under this heading, the quantity of *Heat Demand Density* or *Ground Heat Density*, that is the energy unit per land area, is a possible answer to these questions.

Leading back, once again, to the local nature of the heating and cooling sector, heat demand density may be interpreted as a measure of the concentration of specific building heat demands in a given land area (similar for cold demand density). In this sense, a clear distinction between specific demands (be they by floor area or per capita) and the spatial concentration level of these demands, is of essence to begin resolving the enigma. An instinctive reaction would then be to foster continued densification of already dense urban areas, whereby reduced specific demands would be counteracted to maintain overall heat demand volumes. And vice versa, in low-density areas, typically non-urban, rural settlements likely not to expand into dedicated urban areas, unless perhaps locally clustered into patches of high density, priority should naturally be given all kinds of individual energy efficiency measures since there can be no conflict with central system solutions in such areas.

Heat demand density is in this respect a parameter by which to determine, based on physical evidence, the suitability of different heat supply technologies and types of energy efficiency measures with respect to different locations and spatial circumstances. The quantity of heat demand density may further be used to illustrate the commonly ignored fact that most urban areas in Europe – be they located in northern, eastern, western, or southern, Europe – display principally similar average heat demand density levels inside dedicated urban areas. As one of the last outputs from the Heat Roadmap Europe project series [21], the relationship between population densities in urban areas (above 50 TJ/km^2) and average national per-capita specific heat demands (which by multiplication yields heat demand density), is reproduced for the 28 EU Member States and the year 2015 in Figure 1.

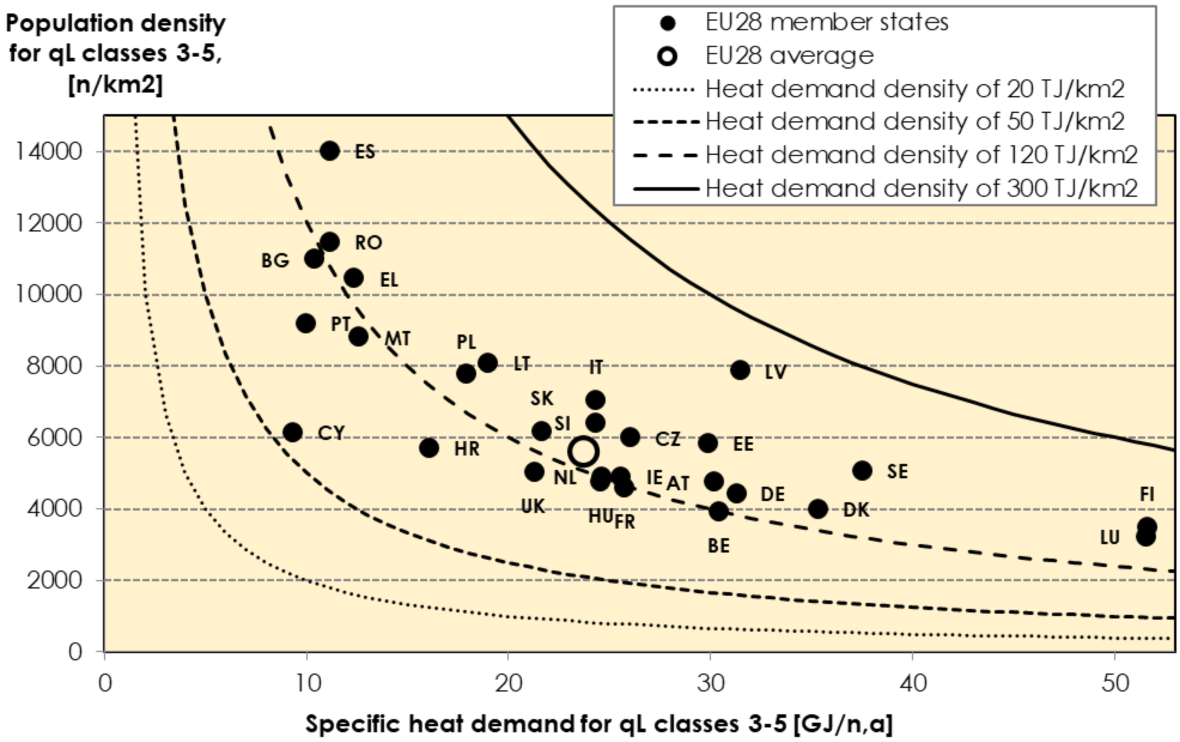

FIGURE 1. ILLUSTRATION OF THE RELATIONSHIP BETWEEN POPULATION DENSITY IN URBAN AREAS AND AVERAGE PER-CAPITA HEAT DEMANDS FOR THE 28 EU MEMBER STATES IN 2015. FREE ELABORATION OF ORIGINAL GRAPH PRESENTED IN [21].

By the establishment of heat demand density intervals, or classes, which in addition may be associated to typically suitable heat supply technologies and solutions, the usefulness of the heat demand density concept is further enhanced. This feature is also represented in Figure 1, where it can be seen, by reference to such classification, that the majority of Member States are placed close to, or in close vicinity to, the 120 TJ/km^2 threshold (which by Danish standard is indicative of general feasibility for network heat distribution [22]). The conclusion being that most European inner-city areas indeed have sufficient concentrations of heat demands in order to facilitate cost-effective district energy solutions. In those Member States where specific heat demands are relatively low, due to warmer climates, population densities are generally much higher, and vice versa, equalling out in rather similar average urban heat demand densities across Europe.

For the above reasons, and others, the quantity of heat demand density is central not only to this report, but, of course, to any effort in the direction of strategic heat planning (similar for cold demand density). As was the case, mentioned above, for the topic of cost-optimum between investments in heat supply and heat savings, the topic of heat demand density is also further elaborated upon in the parallel project deliverable titled *Techno-economical possibilities and system correlations (with pros and cons for the participating cities as input to their local discussions)* (Deliverable 2.3), which is due by project month 12 (June 2021). In addition, heat demand density is treated and discussed in more detail also in section 0 (Feasibility study of a district heating system for Bilbao) of this report, and as well in section 6.3.1, which presents a response to the first of two questions asked by the LWG of Vienna, in this case referring to parameters for deciding to extend DHC grids.

1.1.3. Energy quality and temperature levels

The second thematical concept appropriate to mention here is that of energy quality and temperature levels. The logic for this is that a successful transition to fully sustainable and decarbonised heat and cold supply structures in the future will require not only optimal organisation of infrastructures and systems, but also optimal operation of these infrastructures and systems. The world we live in will never run out of energy, that is impossible and would be in violation of the 1st law of thermodynamics (law of conservation), but it may very well run out of energy quality (exergy, second law of thermodynamics), or at least run short of easily accessible energy quality at the ridiculously low price levels that we have become accustomed to in our day and age[4]. There are a few exceptions, further detailed below, but the general rule should be to always strife to satisfy a demand for energy with an energy supply at the corresponding energy quality level[5].

In the context of building heat demands, which regularly consist of nothing else, but space heating and domestic hot water demands, both well below 100˚C, this rule translates into the strife to meet such demands with energy supplies available somewhere in this temperature range, and certainly not by direct heat-only use of any high-quality energy carriers such as natural gas or electricity. The latter has a name: *Exergy Destruction,* which signifies the use of high-quality fuels and energy sources for low-temperature heat demands, without cogeneration of electricity and heat, and although this is still standard practise in many parts of Europe today, eventually this is synonymous with resource abuse and it is questionable whether it can be tolerated in the long-term perspective. It may be speculative, but in fact both reasonable and quite realistic, that the European community in due time decides to add to its list of effective policy measures also an address on the efficient and adequate use of energy quality (if here neglecting previous acts on e.g. cogeneration [23]).

[4] In commentary here it might be said that if, in the near future, no substantial reductions appear in the cost-competitiveness of consumer prices for traditional energy carriers such as natural gas, fuel oil, petroleum, coal, and electricity generated from such energy sources, the prospects for achieving real transitions towards sustainable and decarbonised heating and cooling supply structures in Europe will be correspondingly limited.

[5] Without entering into a deeper discussion on the topic of exergy and energy quality, a good rule of thumb to understand the concept of energy quality is to ask the question whether the energy source under consideration can make something rotate (can it perform mechanical work)? If the answer to this question is "yes", the energy source is of high quality, if "no", it is of low quality.

But there are no rules without exceptions, and that rule is no exception from this rule. In fact, to be mentioned here, the two most striking exceptions both relate to the use of electricity for low-temperature heating purposes, where, on the one hand, this takes place in individual heat pumps particularly in rural areas (which is acceptable due to the higher conversion efficiency of heat pumps compared to all other individual alternatives, as well as to the lack of access to district energy systems), and where, on the other hand, this occurs in central, energy-sector, large-scale, heat pumps (and other Power-to-Heat applications such as electric boilers), as a means by which to obtain operational synergies through systemic integration between power and thermal sectors. A third exception is conceivable also within the realm of waste management, where waste incineration, even in non-cogeneration mode, may be motivated and acceptable from a pure waste management perspective (to get rid of the waste), and in particular so for hazardous and non-recoverable waste fractions otherwise at risk of being landfilled.

The temperature level of energy assets is not only a determining factor of their energy quality, in terms of exergy content, it is also a key operational characteristic during their supply, distribution, and use in district heating systems. All through the developmental history of commercial district heating technology in the modern era, which stretches back to the late 1870s and the northern parts of New York state in the United States of America [24], a recurring feature has been that of continuously reduced operational system temperatures. This development has found a narrative in more recent years which has introduced the concept of different district heating generations, where, from the interest of this report, the upcoming 4th generation (4GDH), assumed to represent best-available technology from 2020 to 2050, is associated with supply and return temperatures in the order of 70˚C/30˚C, for further reading see references [25, 26].

The reduced operational temperature levels of future district heating systems, compared to current 3rd generation district heating systems (3GDH), 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 be said with respect to the recovery of excess heat, 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.). Furthermore, reduced operational temperatures reduces the average temperature difference to the surrounding ambient, which in turn reduces the amount of distribution heat losses associated with low-temperature heat distribution. For the above reasons, and others, 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, represents a key ingredient in a successful transition.

Temperature levels can be said to be representative of yet another key problematic area which emerges as ordinary fuel combustion as peak load supply ceases to exists as a standard option. What to do during cold spells and winter seasons? Three principal approaches may initially, and in combination, provide realistic solutions to this problem, namely the active use of demand side management (load shifting by various techniques), system integration, and the comprehensive deployment of thermal storages.

1.1.4. Non-technological dimensions

The third thematical concept to be briefly touched upon in this introduction relates to the non-technological dimension of the decarbonisation of heating and cooling supplies. By non-technological dimension is to be understood firstly, as also outlined in Phase 2 of the three-phase framework presented in Table 1, economic and political barriers and opportunities directly related to any given strategic heat plan. Secondly, this relates to involved stakeholders and the proper understanding of their respective interests and perspectives, to the *Best Available Organisation* (BAO) of these stakeholders and actors, to ownership principles, business models, and, in short, the overall design and structure of the transition process. The formulation of a concrete implementation plan, a roadmap, which pinpoints and outlines the successive steps by which to realise the strategic objectives of the heat plan, is of absolute importance.

In extension, there may be many more aspects that could be added to this dimension, although they may not be directly associated with the local group working on the actual strategic heat plan. The value of transparency and active communication with the community is hard to overestimate. If the actions and measures introduced by a local working group to reach the strategic objectives, especially if substantial, perhaps radical and no-regret, are not thoroughly accepted and shared by the community, there will most likely be very little transition taking place. The citizen involvement, the education and instruction, the shared ownership perhaps[6], the teaching of children and elders, all and any activity that may result in a strong and united community which comprehends the rationale and logic for the changes soon to come is, likewise, of great importance for the viability of the plan.

In a wider perspective, moreover, once the curtains are open and the stage of transition is exposed in full view, there is also a deeper and more profound insight to be managed: The collective realisation that a transition of heating and cooling supply structures, while perhaps comprehendible on paper as merely consisting of a few tweaks here and there in the existing system, in fact implies substantial societal change. A full "decarbonisation" of hitherto fossil-based heating and cooling supply structures, as we have built and known them for centuries, represents no less than a major transition, not only of technological systems, but of traditional preferences and lifestyles, of human cultures, of our approach to production and consumption of material commodities, and, at rock-bottom, of our everyday understanding and grip of resource efficiency and sustainability as a general code of conduct.

In this sense, when considering the overall evolution of human kind and man's mode of existence on the planet, there cannot be any fixed target year, as there indeed can be in the case of explicit strategic heat planning (which often is placed some fifteen to thirty years into the future). But there can be the recognition of empowerment by proactive decision-making and foresight, which brings about yet another key concept to behold in this context, namely that of *Critical Choices*. A first order meaning of this concept is of course that decision-making most often is difficult because none of the alternatives at hand are without drawbacks, and, hence, the chosen alternative is seldom the best, but rather the least bad one. However, this concept also has a second order meaning, and this is the acuteness, the criticality, of actually making decisions. The failure to do so, the refusal or incapability to do so, nonetheless equates into a "decision" having been taken: the passive and inactive one.

[6] The Danish example during the 1980s and forward regarding shared ownership as a means by which to stimulate and foster technology acceptance for wind power is an impressive story.

1.1. Objectives and structure

As was briefly mentioned above, this report is the second out of four WP2 accounts relating explicitly to the work within the six LWG's to establish H/C outlooks as part of their respective strategic heat plans, which will result in city-specific transition roadmaps for the year 2050 (implementation plans). For clarity, the four accounts are listed below:

- 1. The initial presentation *Input for H/C outlook 2050* (Deliverable 2.1, confidential, M3, September 2020)
- 2. This report, *Draft recommendations for H/C outlook 2050* (Deliverable 2.2, confidential, M12, June 2021)
- 3. *H/C outlook 2050 of cities with cross-city synthesis* (Deliverable report 2.6, public, M26, August 2022)
- 4. *Recommendations for cities' H/C supplies & demands in 2050* (Deliverable report 2.7, public, M27, September 2022).

The main objective of this report is, as the title suggests, to provide draft recommendations to the LWG's on the establishment of H/C outlooks. The structure of the report therefore begins with an introduction to strategic heat planning and some general key concepts related to the decarbonising of heating and cooling. Next, the report presents one separate chapter for each of the six cities, all structured similarly with a brief overview of the current situation, with special focus on heat demand density (city maps have been created on the basis of data available from other EU projects and sources), next a concentrated summary of the H/C supply outlooks 2050 (that each LWG has presented under Milestone 2 (MS2, project month 11, May 2021)), and, finally, draft recommendations in response to these preliminary outlooks, with special focus on local heat resources (city maps have been created similarly as for heat demand densities based on data from previous studies). The report then ends in a summary section with some concluding remarks. Noteworthy, the extent and depth of the city presentations and the associated draft recommendation may differ depending on the developmental stage and current level of progress of each local working group.

During only the first year of its operation, the project and its partners have already engaged in several consortium meetings and capacity building activities, such as workshops and webinars, in which topical areas of particular interest have been identified and addressed. One such area of interest has been the question of how to transform current urban heat markets dominated by individual natural gas supplies. Another area has been that of deep geothermal resources and how to exploit such resources in dense urban areas with limited land accessibility. A third area of interest has been that of data access, reliability, and management, in particular geospatial data, as a prerequisite for strategic heat planning. As a result of the uniqueness of local conditions, and again, in the recognition among the project partners that each of them indeed have unique interests and concerns, it was suggested during a Steering Group meeting in the early spring of 2021 that each of the six cities could formulate and raise two questions each – two questions that WP2 then would contemplate and provide answers to as part of their recommendations on the heating and cooling outlooks for 2050.

In the preparation phase of this report, and its parallel deliverable presentation D2.3 (Techno-economical possibilities and system correlations (with pros and cons for the participating cities as input to their local discussions)), which has been taking place in the period from April to June 2021, WP2 has received such questions from two of the six LWG`s, namely from Bilbao and from Vienna. We have taken the opportunity to analyse these questions in more detail and have included two additional subsections in this report where our responses to these questions are presented.

The first subsection (2.3 Feasibility study of a district heating system for Bilbao) has been placed under the main section on Bilbao (section 2) and consists rather of a principal, and comprehensive, response to Bilbao's H/C supply outlook for 2050, where electrification of the entire heating and cooling sector is in sole focus. We believe that this response may be of particular interest also for the other project partners and have, for this reason, chosen to include that here while instead present our answers to the more general questions raised by Bilbao in the public Deliverable 2.3 presentation. The LWG of Bilbao raised the following questions:

- Q1: To reduce natural gas dependency in Bilbao, should electrification of the heat demand be promoted over deep building refurbishment? Socio-economic benefits of the two approaches towards decarbonization need to be assessed.
- Q2: With the fluctuating electricity prices and the upcoming energy flexibility markets, could cost-effective energy flexibility measures be implemented at districts or building level (e.g. building or district heat storage, electric storage).
- Q3: What will be the role of H2 in the future energy supply of Bilbao's buildings? Should we explore integration of H2 into current gas pipelines, or other options such as fuel cells for Micro-CHP in buildings?

As for the city of Vienna, the second additional subsection in response to LWG questions (0 Responses to Vienna LWG questions) has been placed under the main section on Vienna (section 6) and answers the following two specific questions raised by the local working group in Vienna:

- Q1: Parameters for deciding to extend district heating and cooling (DHC) grid (section 6.3.1)
  - Under which conditions (in which areas) is district hearting always the best option? Under which conditions (in which areas) is it most likely never a good option? Under which conditions/parameters is DHC potentially a good option to be explored?
- Q2: Making DHC "future-proof" / needs of utility (section 6.3.2)
  - What models exist (in Sweden?) that can help utilities to make DHC more competitive and a good future-proof option? Is time- or temperature-dependent DH tariffs a possibility and how to implement them?

Regarding the four cities from which no questions were received at this time, Dublin, Munich, Rotterdam, and Winterthur, may look forward to WP2 responses to possible questions as part of the reporting in association with the third and fourth WP2 accounts on the H/C outlooks next year, that is in the *H/C outlook 2050 of cities with cross-city synthesis* report (Deliverable 2.6) and in the *Recommendations for cities' H/C supplies & demands in 2050* report (Deliverable 2.7). At this stage, therefore, no separate sections with answers have been included for these four cities neither in this report nor in the parallel Deliverable 2.3 presentation.

1.2. Scope and limitations

One of the main features of strategic heat planning is the geographical mapping and spatial analysis of heat and cold market parameters. By incorporation into dynamic Geographical Information Systems, data, statistics, and, in principal, any piece of information for which a spatial reference can be established, can partake, and contribute to increased knowledge and understanding of the characteristics and opportunities pertinent to our local heating and cooling markets.

As this report presents several maps which portrait such local heating and cooling markets, i.e. local conditions in the six project cities, but which were not the result of the work among the local working groups, it should be made clear that these maps are included here mainly for illustrative, directional, and tentative purposes – as overview references for the LWG's to steer by as they leave port. The reason for this is that the underlying data used to produce these maps typically originate from continental level analyses, where generic approaches have been used to assess demands and supply potentials uniformly on e.g. EU Member State level. These data may still be of value also for local projects, but they cannot, and should not, replace the local level data needed for the creation of detailed strategic heat plans at city levels. As a matter fact, the gathering, management, rendering, and analysis, of locally derived data is one of the essential exercises that need to be part of strategic heat planning.

As a mode of expression, draft recommendations presented in this report may take the form of suggestions, such as densification strategies in less dense cities or city districts, or prioritisation schemes, for example in support of industrial excess heat recovery and new district heating systems in urban areas rich of such resources and conditions. Draft recommendations may alternatively also be expressed as rhetorical questions, by which to draw attention to alternative opportunities perhaps at first not appreciated, or by which to emphasise that further analysis will likely be requested for a given, but at first poorly conceived, solution. Recommendations may further be expressed in the form of concentrated bullet lists, where appropriate, or in more elaborated form.

However, either which way these draft recommendations are formulated in the following, they are intended as constructive and helpful responses to the ongoing work within the participating cities. Despite this, we believe that a general disclaimer is in place here to emphasise that we as authors takes no responsibility for how these recommendations may be interpreted or used, nor can we guarantee the accuracy or usefulness of the information contained in this document, nor that use of such information is free from risk, and we will therefore accept no liability for any loss or damage experienced by any person and/or entity using this information.

2. Bilbao

By presentation in alphabetical order, the Spanish city of Bilbao is the first of our six cities to get acquainted with in more detail. As can be seen in the map of Figure 2, 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, current annual heat demands for space heating and domestic hot water preparation in residential and service sector buildings in Bilbao are characterised by high levels of spatial concentration.

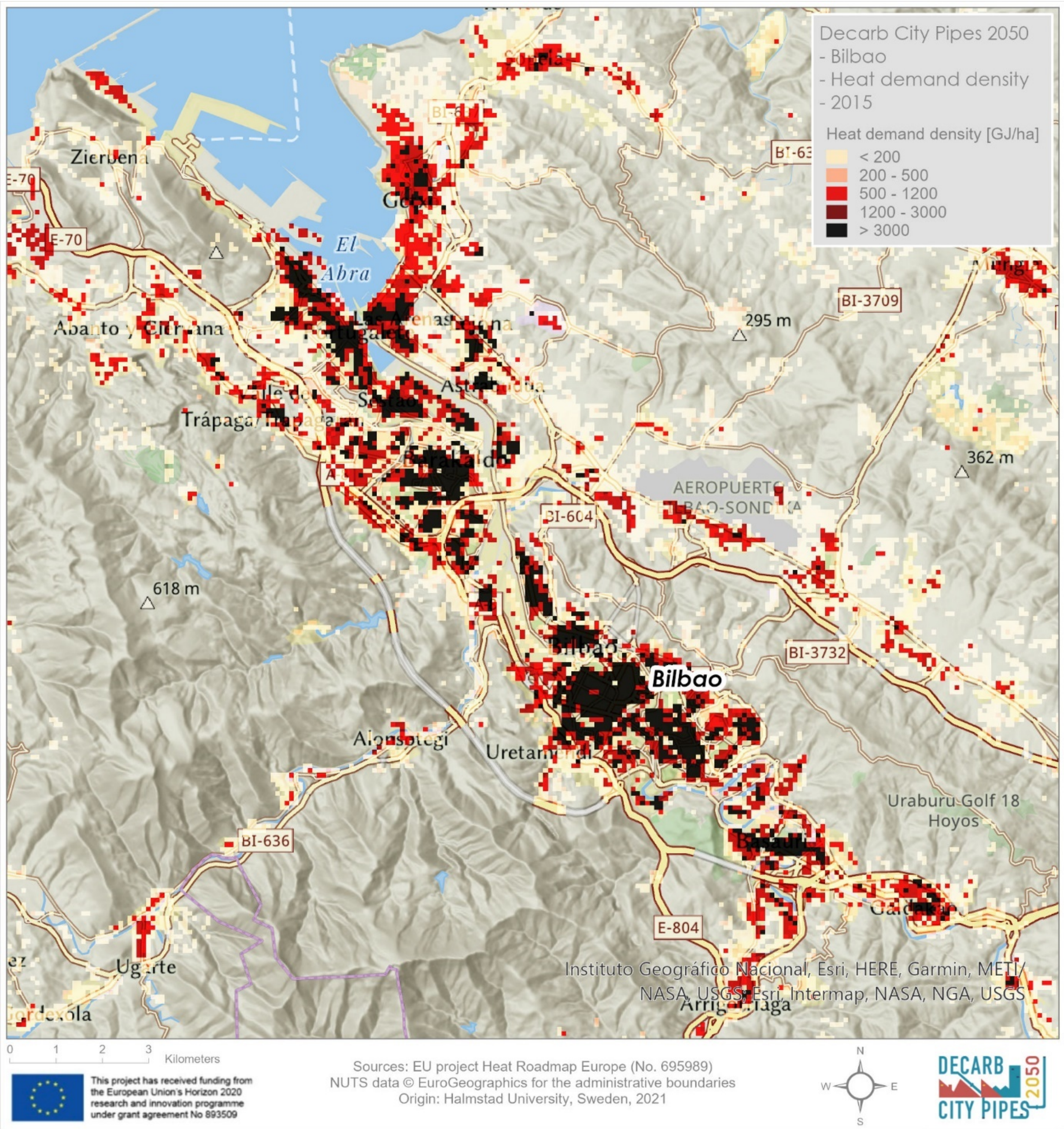

FIGURE 2. MAP OF HEAT DEMAND DENSITY BY HECTARES IN THE CITY OF BILBAO AND SURROUNDINGS. SOURCES: [9, 27].

The local working group in Bilbao, which is led by the Commission for Mobility and Sustainability under the city administration, is divided into two parts: a political commission (decision-making body consisting of city councillors) and a technical commission (core group of technical municipal departments). The Commission for Mobility and Sustainability is in charge of the city's energy transition process and collaborates with municipal departments and institutions that already have strong roles in the city development (such as within housing, retrofitting, ICT' s, employment etc.). The commission also collaborates with regional institutions (such as within energy and environment, water, and waste management etc.) as well as with utilities, distribution system operators (DSO's), and other external stakeholders.

According to the information shared by the local working group of Bilbao under Milestone 2 of the project (H/C supply outlooks 2050)[7], annual greenhouse gas emission from the city have been steadily declining since 2005, as can be observed in Figure 3. The total annual volume according to the last inventory (2018) is stated at 1004 kilotonnes CO_2-equivalents and there has been a 37% reduction of greenhouse gas emissions during the presented time period.

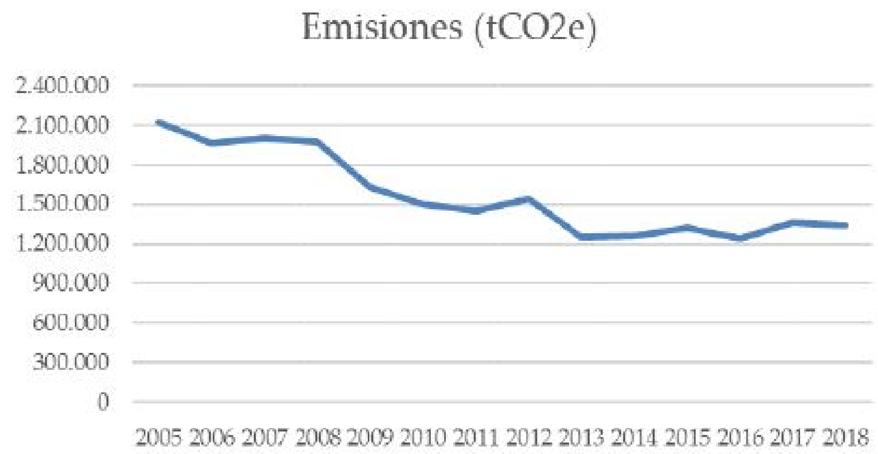

FIGURE 3. DEVELOPMENT TREND OF GREEN HOUSE GAS EMISSIONS SINCE 2005 IN BILBAO.

The main challenges identified relates to the decarbonisation of thermal consumption, that is, how to integrate more renewable energy sources (RES) in a heating and cooling supply which currently consist of more than 90% natural gas (740 GWh). In the first draft version of their H/C outlook, the Bilbao LWG states a total heating and cooling consumption in 2018 amounting to 807 GWh (543 GWh for space heating and 264 GWh for doemstric hot water), and these volumes are later broken down by residential and non-residential sectors, as well as by fuels and energy sources. Cooling is stated as having a low impact on the city, with 136 GWh stated as mainly consumed in tertiary buildings for the reported year.

An important aspect of the work in the LWG has been to initially identify Bilbao's biggest obstacles, and possibilities, with respect to decarbonisation of thermal consumption, where,

[7] The information shared by the participating cities under this milestone is, as this report, internal and not intended for publication. The data and statistics presented with reference to the cities' H/C outlooks in this report, under this sub-heading for the city of Bilbao and under corresponding sub-headings for the other cities, relies entirely on this shared information and no further references will be given here to the presented data. In some instances where the local working groups have given source references as part of the shared information, these sources may be mentioned also here. As for content, only key numbers and elements from the shared information have been selected for presentation in this report, which includes the reuse of some graphic materials and images. The full scope and detail of the H/C outlooks being developed by each city will become available in various formats as the project progresses.

on an administrative level, other issues such as general environmental problems related to water and soil contamination, historically has had higher priority. The Bilbao LWG recognises that they have limited knowledge on how to make this kind of transition happen (who doesn't?), but also that the city has valuable knowledge and experience in several areas that can add great value to the process, for example in industry and sustainable mobility. As an indicative first analytical approach, the LWG states that is has conceived of a 4-step methodology, bottom-up, which starts at the building level, then goes on to a group-of-buildings level, then to a level of "city areas", to end in a city-wide view.

The city as such has also committed itself to an environmental strategy, the Bilbao Environmental Strategy 2050, which aims to achieve carbon neutrality by 2050 and to improve the city's life quality. The strategy aims as well at, what is labelled, "climate change adaptation", which is stated to imply, among other things, a cut in half of the risks associated with climate change. The city has further recently renewed its Covenant of Mayors commitments (12/2020) under their Sustainable Energy and Climate Action Plan (SECAP 2030), which targets a 40% GHG reduction by 2030. By the Basque Sustainable Law, under which the city is obliged, public authorities should further reduce their energy consumption by 35% (2030) and by 60% (2050) and the RES share in public buildings should be 32% by 2030.

2.1. Heating and cooling outlook 2050: Bilbao

As for their draft H/C outlook, the LWG of Bilbao has chosen to analyse thermal consumption in the city by residential and non-residential sectors respectively. For the residential sector, a total final consumption heat demand in 2018 is stated at 260 GWh for space heating and 185 GWh for domestic hot water, which results in a total final consumption of 445 GWh/a for this sector. The distribution of different types of heating supplies in the residential sector, as depicted in Figure 4, reveals a very low penetration of heat pumps (<1%), below 30% of centralized systems, 15% direct use of electricity (Joule). and more than 50% of the area supplied with individual gas boilers.

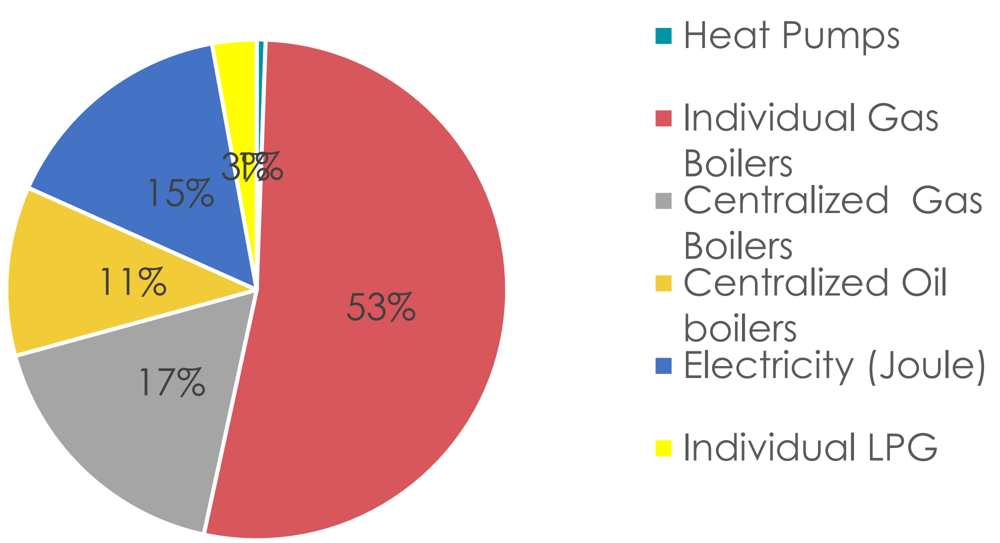

FIGURE 4. TYPE OF HEATING SYSTEMS IN RESIDENTIAL BUILDINGS (BY % OF HEATED AREA).

For the non-residential sector, the corresponding distribution of different types if heating supplies are given in Figure 5, and by main non-residential sub-sectors in Figure 6.

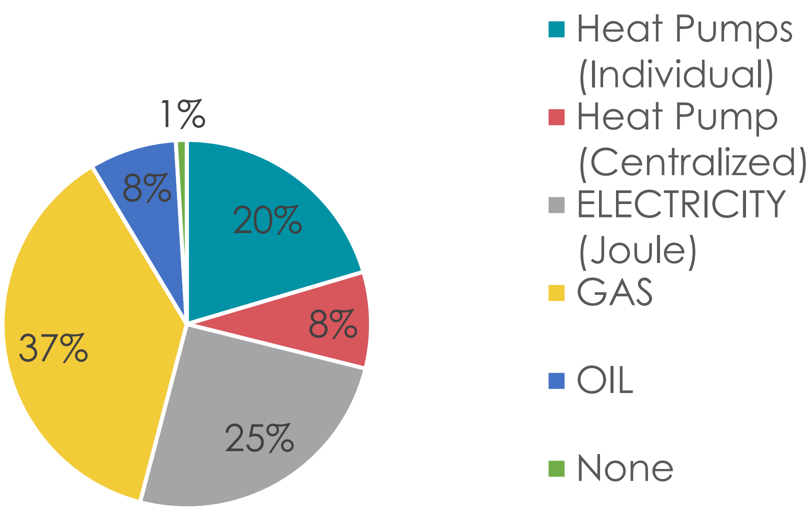

FIGURE 5. TYPE OF HEATING SYSTEMS (% OF ALL NON-RESIDENTIAL HEATED AREA).

The total non-residential sector final consumption heat demand in 2018 is stated at 282 GWh for space heating and at 79 GWh for domestic hot water, which renders a total of 361 GWh/a for this sector. As stated above, this equates to a total final consumption heating and cooling demand in Bilbao at approximately 807 GWh per year.

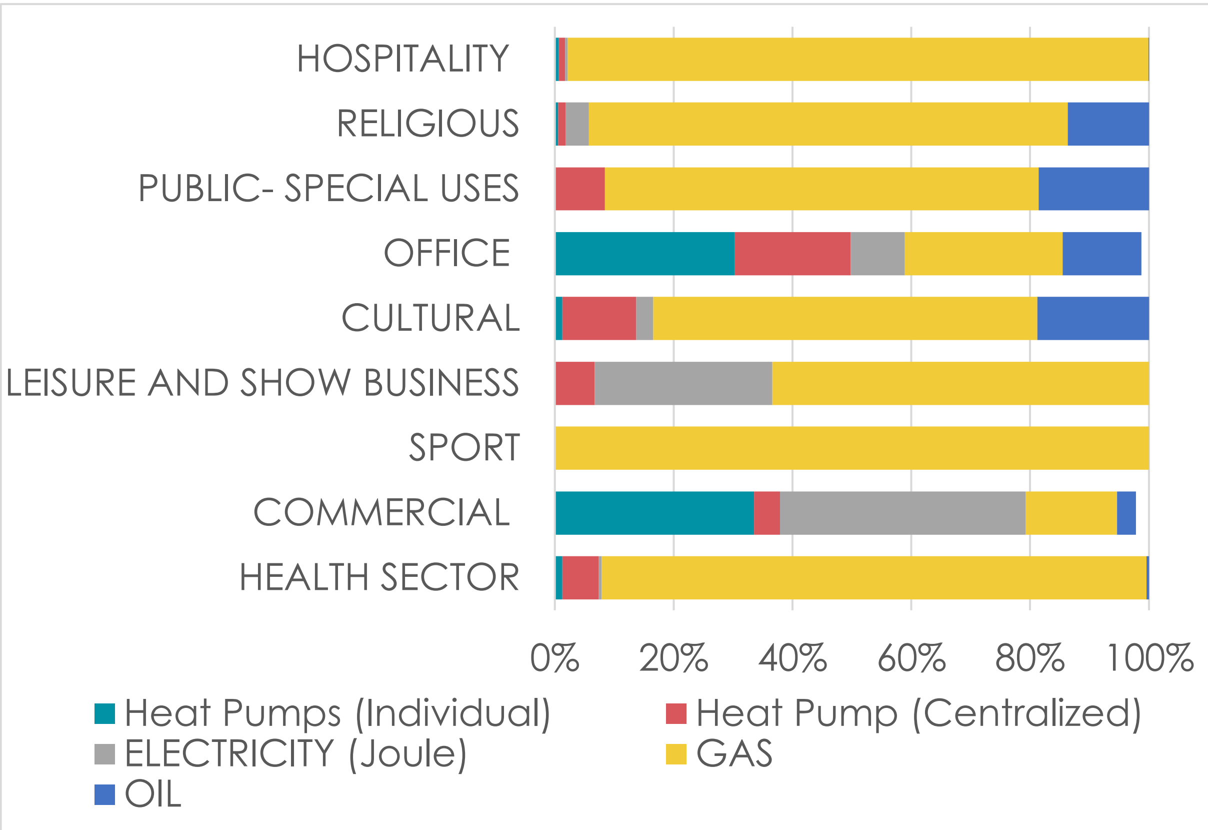

FIGURE 6. TYPE OF HEATING SYSTEMS – NON-RESIDENTIAL BUILDINGS - % OF HEATED AREA.

The anticipated transition from this current situation towards 2050, builds in the case of the local work group of Bilbao, essentially on a comprehensive shift from individual and central use of natural gas to a total electrification of all thermal consumption in the city. In addition, some degree of heat savings in buildings are foreseen as well as the possibility to obtain reductions in final consumption demand by behavioural changes.

In the residential sector, for which the situation in 2018 and that assumed in 2050 is outlined in Figure 7, an increase in the housing stock of about 20% is anticipated for 2050 together with an assumption that approximately 25% of all buildings have been refurbished by that year. More than 50% of the building stock is thought to still be associated with relatively high energy demands for heating (>20 kWh/m2 year). As for the existing H/C systems, all (100%) are assumed to have been renovated by 2050, and there will no longer be a natural gas network with access to residential buildings in Bilbao in the future.

Hence, all space heating and domestic hot water demands for residential buildings will be fully electrified by 2050. The solutions to accomplish this consist of the combination of centralized heat pumps (aerothermal or connected to low-temperature sources), individual heat pumps (aerothermal), and direct electric heating (Joule effect). Energy demand for cooling will increase, as it could be supplied by some of the heat pump systems, but will remain comparatively low.

For space heating, the LWG of Bilbao suggest that, for this to happen, 50% of current individual space heating combustion systems (gas and LPG) will be changed to individual aerothermal heat pumps, and the other 50% to direct electric heating systems (Joule Effect), and all current centralized gas and oil boilers will be substituted by centralized heat pumps. As for domestic hot water, 75% of current individual DHW systems will be changed to individual heat pumps, and 25% to direct electric heating systems (Joule Effect), and all centralized DHW systems will be substituted by centralized heat pumps.

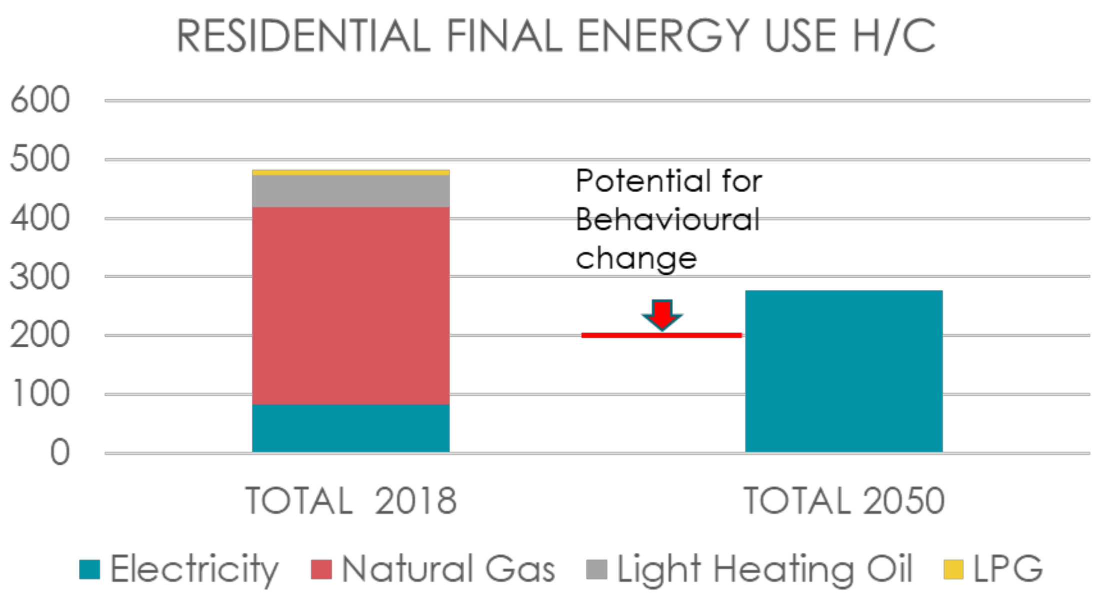

FIGURE 7. H/C OUTLOOK 2050 BILBAO: RESIDENTIAL SECTOR FINAL ENERGY USE IN HEATING AND COOLING BY TYPE OF HEATING IN 2018 AND IN 2050.

In the non-residential sector, similarly, see Figure 8, space heating and hot water demand is assumed to remain constant, where new areas added are compensated by refurbishments of building envelopes in existing buildings), and where, as for the residential sector, all (100%) of the existing H/C systems will be renovated by 2050. For this sector as well is foreseen a complete electrification (both for space heating and for domestic hot water). The conceived solution will combine centralized heat pumps (aerothermal or connected to low temperature sources), individual heat pumps (aerothermal), and direct electric heating (Joule effect), just as for the residential sector.

Cooling demand, however, is anticipated to increase due to causes such as climate change effects and comfort expectations. The total electricity use for cooling, however, is expected to remain constant since new cooling systems are expected to operate at increased efficiencies, partly due to renovation, and partly by the potential to connect to low temperature networks and sources). For space heating, all current centralized gas and oil boilers will be substituted by centralized heat pumps and 25% of current electric heating will change to heat pumps. For domestic hot water, all current centralized gas and oil boilers will be substituted by centralized heat pumps and 50% of current electric DHW systems will be changed to individual heat pumps. IN 2050, a natural gas network will not exist for non-residential buildings.

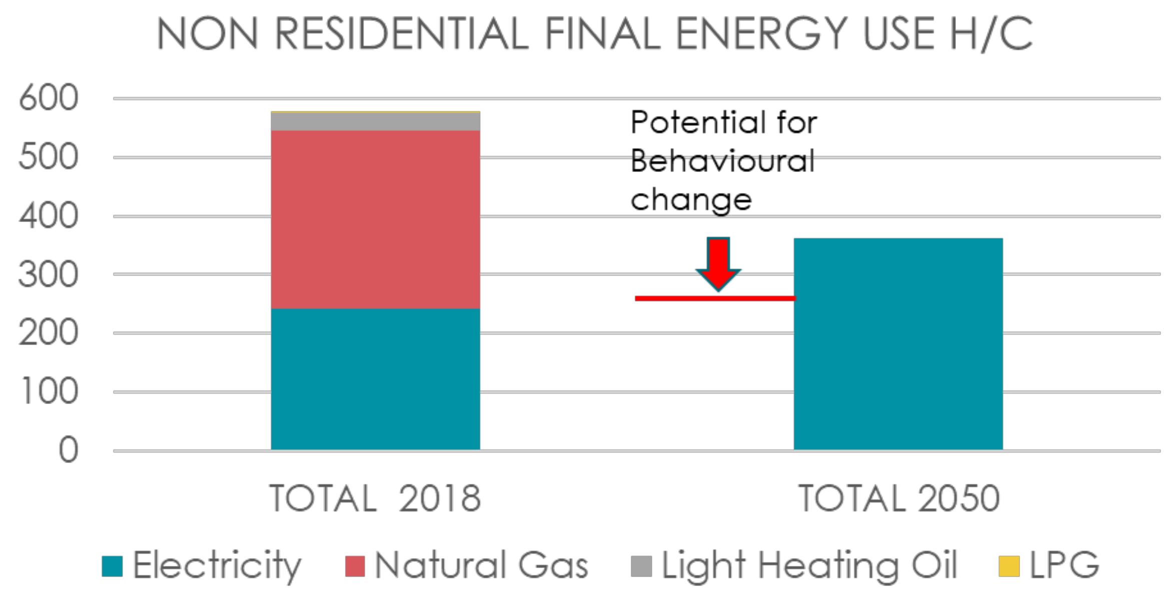

FIGURE 8. H/C OUTLOOK 2050 BILBAO: NON-RESIDENTIAL SECTOR FINAL ENERGY USE IN HEATING AND COOLING BY TYPE OF HEATING IN 2018 AND IN 2050.

2.2. Draft recommendations: Bilbao

For the specific case of Bilbao, the authors have taken special notice, both of the shared information and of the explicit questions asked, and therefore prepared a comprehensive response in the form of a feasibility study for DH in Bilbao (as presented in the next section). Since this response comprises principally all aspects of concern that could be put forward as relevant recommendations, there is not so much else to add here.

However, interestingly, two additional remarks may still be included here to put emphasis on two areas of opportunity for Bilbao. The first of these remarks relate to the notion of “energy demand management”, which the LWG itself mentions as a future possibility in support of full decarbonisation. We recognise this and strongly recommend further studies and analysis of the potential for energy savings from behavioural change, be it the result from awareness campaigns, regulatory measures, subsidies, rewards, fines, or perhaps from other educational activities. Awareness-raising campaigns, such as training of municipal workers which could extend to citizens, are apparently already in progress and this is promising.

Finally, in view of the suggested plan for a full electrification of the complete thermal sector (without any alternatives being mentioned), we ask the LWG of Bilbao to at least take a good look at the map presented in Figure 9. If there ever were a city somewhere in Europe that wished it had better conditions for building a city-wide district heating system, and we know that there are more and more such cities today, anyone could say: "- Look at Bilbao in northern Spain! Not only is it a city with high heat demand densities coherently distributed within it, it also hosts a number of conventional as well as unconventional excess heat resources that could be utilised to form a fundamental basis for decarbonising its city pipes".

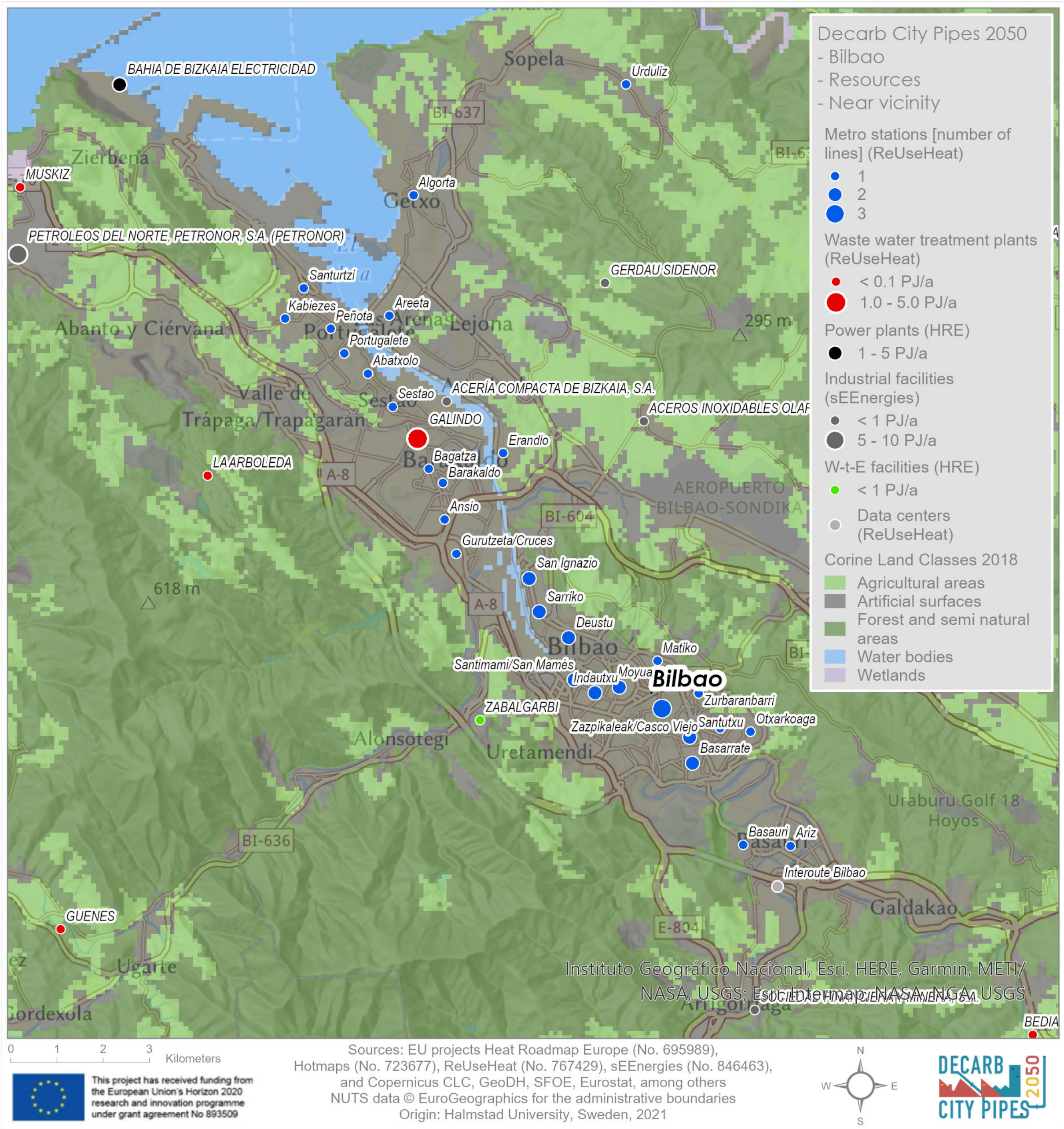

FIGURE 9. EXAMPLES OF HEAT RESOURCES IN BILBAO AND ITS NEAR VICINITY. SOURCES: [9, 12, 13, 28].

2.3. Feasibility study of a district heating system for Bilbao

The aim of this feasibility study is to analyse the economic feasibility of DH as a means for decarbonising Bilbao's heat supply. The study analyses the three main cost components of deploying a district heating system; distribution, heat supply, and connections to consumers, and shows that a district heating system could be economically developed thanks to two main reasons. On the one hand, the high heat density of the city allows for an economic distribution network and, on the other hand, the availability of industrial waste heat in the vicinity of the city. A district heating network could supply up to 80% of the heat demand (800 GWh/a) with an average distribution cost of 18 €/MWh, a production cost of 41 €/MWh and a conversion cost per household of 2.700 €, equivalent to 37 €/MWh, totalling 96 €/MWh. This solution would be competitive with an electrification of the heat supply by heat pumps and considerably cheaper than a Joule heating solution.

In environmental terms, the proposed district heating system would trigger a substantial reduction of the carbon emissions in the city compared to the current heat supply. Moreover, the district heating solution could bring about concomitant benefits such as increasing the competitiveness of industrial companies located in the surroundings of the city. In addition, the system would pave the way for the utilization of future sources of waste heat such as hydrogen production. However, the DH system solution would need to compete with the incumbent heating option, natural gas, which under the current circumstances has a lower marginal cost. The implementation of the new Fund for the Sustainability of the Electric System and a European Carbon tax would contribute to closing this gap, but it is likely that additional financial/regulatory measures need to be put in place.

2.3.1. District Heating Cost Analysis

2.3.1.1. Technical assumptions

In this report it will be assumed a 3rd Generation District Heating System with system temperatures in the range of 70°C-80°C for the supply temperature and 40°C-50°C for the return temperatures. These temperatures are the state of the art in Denmark and Sweden and if adequate measures are implemented, it would be feasible to achieve them.

Operation data from Spanish District Heating systems is scarce but anecdotal evidence suggests that they operate with higher temperatures and lower temperature differences. This should be avoided by all possible means since the production cost of the sources chosen is highly sensitive to the system temperatures, and a lower temperature difference would increase the cost of the network.

2.3.1.2. Economic assumptions

All the calculations in this study have been performed assuming the following parameters:

- Amortisation period: 20 years.
- Interest rate: 3%.
- Annuity of 6,7%.

The amortisation period is considerably lower than the technical lifetime of the distribution network, since current pre-insulated pipes are expected to last at least 50 years, but it has been deemed as reasonable from a private perspective. With respect to the production units, it is somewhat lower than the usual lifespan of 25 years for many of the production units considered.

2.3.1.3. Distribution

The cost of the distribution network has been calculated thanks to the methodology developed by Persson and Werner [29] and used previously in the Heat Roadmap Europe project [21] and improved in the sEEnergies project. It provides a first order assessment for the cost of the distribution network and the service pipes[8], that needs to be further explored with detailed hydraulic calculations. It must be highlighted that an implicit assumption of this method is a 100% connection rate, i.e., all the buildings at range of the district heating pipe are connected. This is not very conservative, but it is the most logical approach since the highest cost stems from additional metres of pipe rather than a larger diameter to supply more customers.

2.3.1.3.1. Method

The estimation of the specific distribution costs of District Heating (€/MWh) in a given area may be done with the following formula:

$$C_d = \frac{C_T}{Q_s} = \frac{\frac{C_T}{L}}{\frac{Q_s}{L}}$$

Where:

- C_d is the specific construction cost per unit of heat sold. It can be annualised considering the period of amortisation and the interest rate
- C_T is the total construction cost for a given area
- Q_s is the total heat sold in a given area
- L is the total pipe length in a given area.
- Q_s/L is the linear heat density, this is the ratio between the heat sold and the total pipe length. This parameter is critical, not only in the determination of construction costs, but also on the proportion of heat losses in a DH network [30].
- C_T/L is the average installation cost per meter of pipe.

If the installation cost of district heating pipes can be expressed as a linear function of the diameter, which is a good approximation (see Figure 10), it can be demonstrated that the average installation cost per meter of pipe can be estimated from the average pipe diameter in the area:

$$C_T/L = m * d_a + n$$

[8] The pipes that connect the distribution network to each building.

Where:

- d_a is the weighted average diameter (weighted by the length of pipes).
- m and n are the regression parameters of the cost curve (4,1572 €/m·mm + 440,63 €/m respectively according to Figure 10).

According to Persson and Werner [29] there exists an empirical relationship between the linear heat density and the average diameter in an area as can be appreciated in Figure 11.

$$d_a = a \cdot ln\left({}^{Q_s}/_{L}\right) + b$$

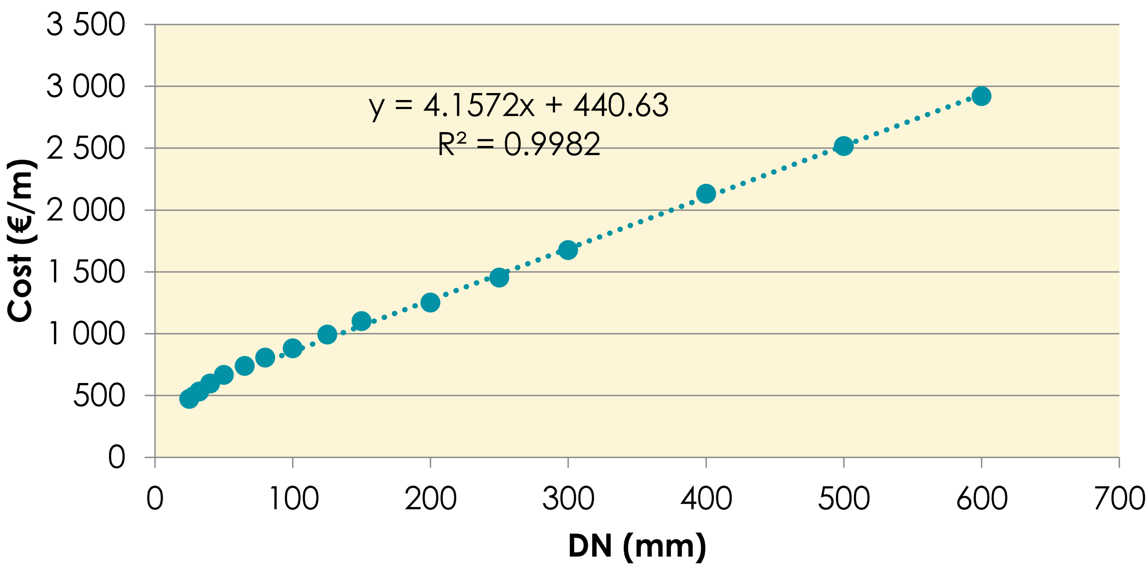

FIGURE 10. DISTRICT HEATING PIPE INSTALLATION COSTS IN CITY AREAS IN SWEDEN. SOURCES: [31, 32].

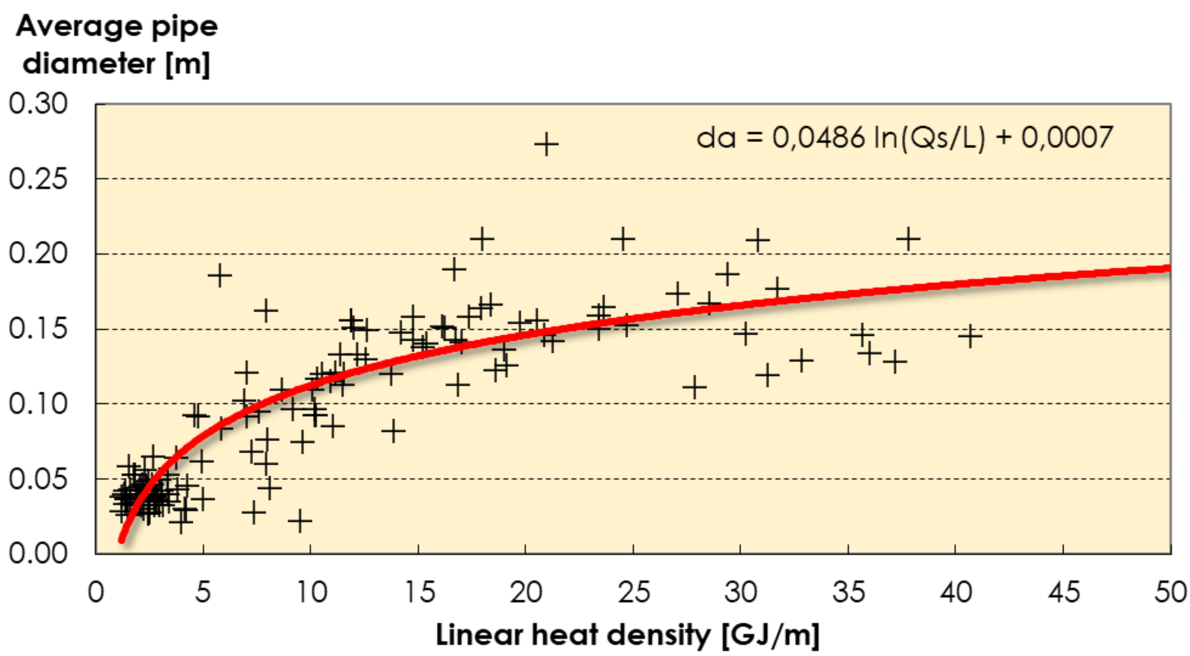

FIGURE 11. AVERAGE DIAMETER AS A FUNCTION OF THE LINEAR HEAT DENSITY. ELABORATED ON THE BASIS OF SOURCE: [29].

It is only possible to determine the linear heat density if the two parameters which compose it, the sold heat, and the total pipe length, are known. Unfortunately, whilst it is relatively easy to assess the heat demand in an area based on the building stock, the total pipe length required for the area cannot be readily estimated. This problem led to the search for empirical methods. One of these methods is based on the effective width concept, initially developed by Werner [33]. The effective width is defined as the ratio between the land area and the trench length in the given area, and its knowledge would enable determining the linear heat density as presented below:

$$\frac{Q_s}{L} = \frac{Q_s}{A_f} \cdot \frac{A_f}{A_L} \cdot \frac{A_L}{L} = q \cdot pr \cdot w = q_L \cdot w$$

Where:

- A_f is the floor area.
- A_L is the land or ground area.
- q, is the specific heat demand, this is, the amount of heat per unit of floor area.
- pr, is the plot ratio, this is, the quotient between the floor area and the ground area.
- q_L, is the heat demand density or ground heat density, this is, the amount of heat per unit of ground/land area.
- w, is the effective width, defined as the area covered by a meter of DH pipe.

The sEEnergies project has produced the following estimates for the effective width as a function of the plot ratio based on a study of Scandinavian district heating networks:

- Distribution pipes

$$w = max\left(\frac{e^2}{pr}, e^4\right)$$

- Service pipes

$$w = max\left(\frac{e^2}{pr}, e^{\frac{ln(pr)-3.5}{0.7737+0.18559 \cdot ln(pr)}}\right)$$

2.3.1.3.2. Data

This study has utilised three different sources to estimate the heat demand density, q_L, and the plot ratio, pr.

- Heat Roadmap Europe project [27, 34]
- Hotmaps [35, 36]
- Cadastre from Bilbao [37].

Datasets from the first two data sources have been utilised as delivered by the respective projects, but the third data source has required a more in-depth analysis. The Cadastre of Biscay provides a shapefile containing all the municipality's buildings together with a CSV-file with information of all the city's units (dwellings, commercial premises etc.) and a common reference to link them. The treatment of the data can be summarised in the following steps:

1. Assessing the likely heated areas and the non-heated areas thanks to a field that indicates the purpose of each unit.
2. Link of the total heated and non-heated areas per building to the building shapefile.
3. Calculation of the total heat demand per building assuming a specific heat demand of 40 kWh/m^2.
4. Allocation of the buildings' information (heat demand and floor area) to the same grid cell as Hotmaps, in order to be able to make a comparison of the different datasets.

This process is rather simple, and it could be greatly improved using different specific heat demands for different building archetypes or building purposes. An interesting example of the first is provided by Fernández et al. [38] for the city of Bilbao, whereas Sánchez-García [32] has studied possible specific heat demands for different buildings usages in another city of Northern Spain. However, notwithstanding possible enhancements, the model provides a total heat demand similar to that indicated by the city and only 20% lower than the heat demand suggested by the Heat Roadmap Europe and Hotmaps projects. Furthermore, at these high levels of heat density, the distribution costs are not very sensitive to possible variations of the heat demand and plot ratio.

Concerning the piping costs, these have been taken from the sEEnergies project. The intercept of the linear equation is 354 €/m, and the slope is 4,314 €/m·mm.

2.3.1.3.3. Results

In Figure 12 it has been depicted the accumulated heat demand sorted by distribution cost. As it can be appreciated, the heat demand is highly spatially concentrated. For instance, approximately two thirds of the 800-1000 GWh heat demand is located in 500 ha, which account for only 6% of the municipality's territory (8100 ha). This resulting average heat density in these 500 ha is 1200 MWh/ha, which is much higher than the usual rule-of-thumb threshold for direct District Heating Feasibility of 500 MWh/ha [30].

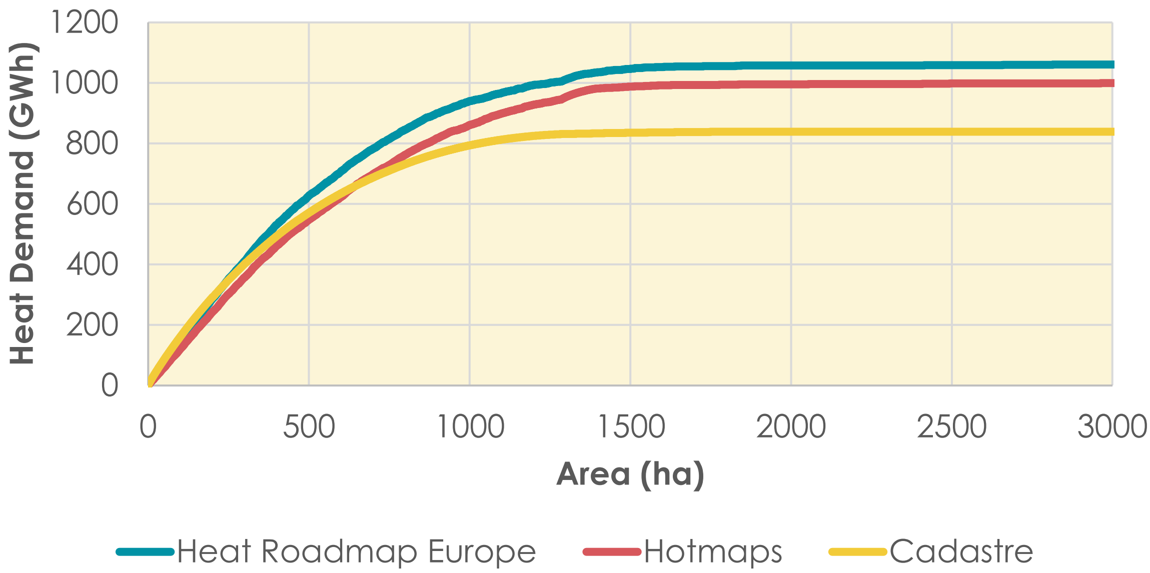

FIGURE 12. CUMULATIVE HEAT DEMAND SORTED BY THE CADASTRE DISTRIBUTION COST.

This average heat demand may be compared to the heat densities shown in Figure 13 for two Danish cities, Aarhus, and Odense. It can be seen that the heat demand densities in these two Scandinavian towns are higher in the city centres but lower than in Bilbao on the outskirts due to the presence of extensive suburbs composed mainly of single-family homes and open blocks. Despite these lower heat densities, the district heating systems serve the entire urban areas to take advantage of the presence of waste heat.

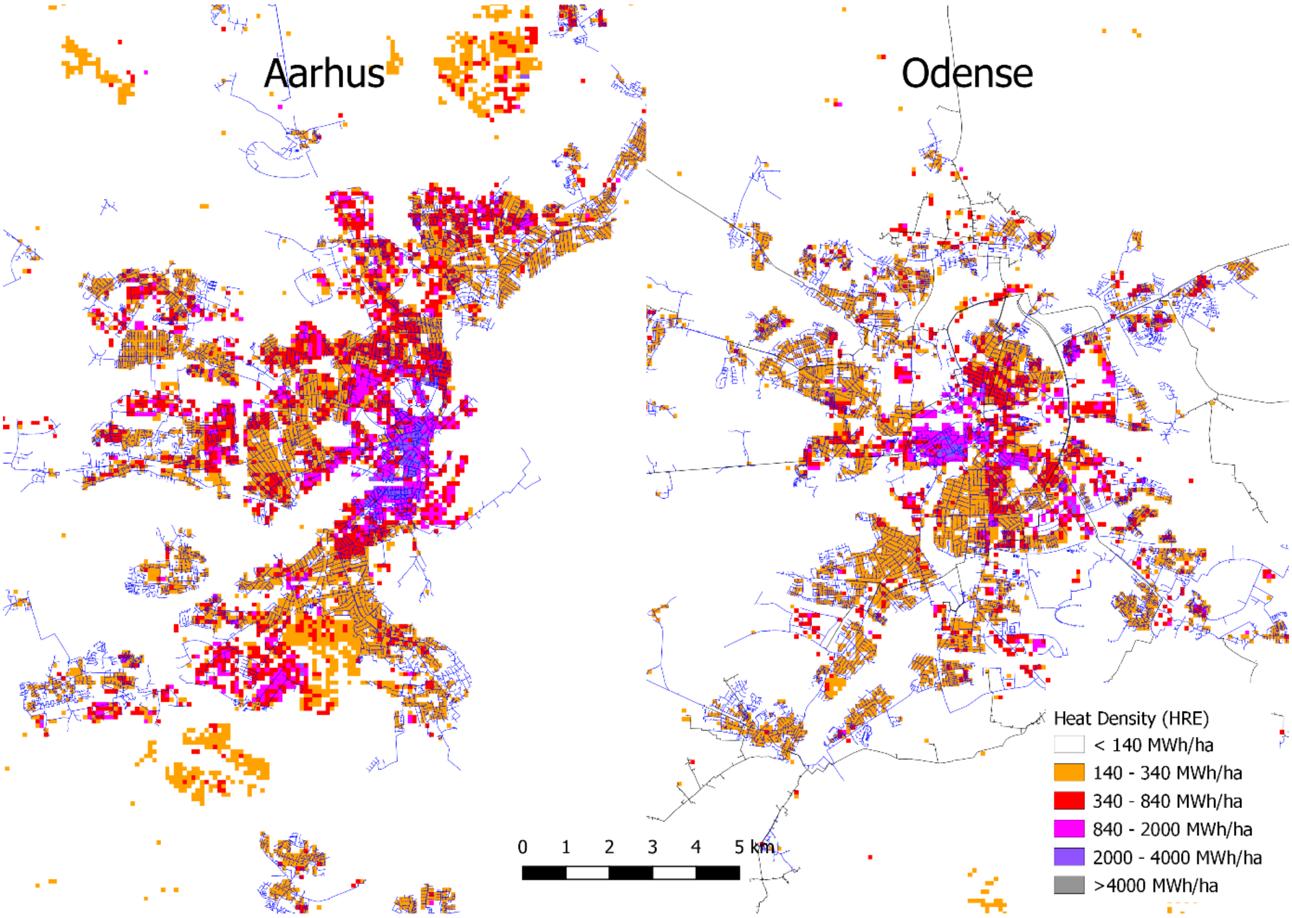

FIGURE 13. HEAT DENSITY AND DISTRICT HEATING NETWORKS OF THE DANISH CITIES OF AARHUS AND ODENSE.

Despite the rather different climatic conditions (3.000 degree-days in Denmark vs. 1.400 degree-days in Bilbao), these similar heat densities result from a much higher concentration of the building stock in Bilbao, which is in alignment with the generic EU Member State level analysis of population densities and specific heat demands presented above in Figure 1. For instance, the average population density[9], a proxy for the building stock, reaches 54.662 inhabitants/km^2 in Bilbao, whereas in Aarhus, it drops to 7.734 inhabitants/km^2.

These high heat densities lead to relatively low distribution costs, as depicted in Figure 14 and Figure 15. The first of these figures present the marginal cost of developing district heating, i.e., the cost of building the network in every single hectare. The three different projects provide different values for each hectare due to the different inputs for Heat Demand

[9] This population density is the population weighted density, which the JRC defines as “a metric which measures the density at which the average citizen lives. It is calculated by taking the weighted average of the density of all parcels of land that make up a city, with each parcel weighted by its population (using the formula D=Σ(Pidi)/ΣPi, where D is the population-weighted density of a metro area and Pi and di the respective population and density of each “parcels”)”. It has been calculated thanks to this dataset, which indicates the population at a hectare level: Freire, S., M. Halkia and M. J. E. C. Pesaresi, Joint Research Centre Dataset PID: http://data. europa. eu/89h/jrc-ghsl-ghs_pop_eurostat_europe_ra. GHS population grid derived from EUROSTAT census data (2011) and ESM 2016.

and Floor Areas, but the overall results are similar, especially in the cheapest areas. The largest difference lies above 600-700 GWh; the cost of building district heating according to the Cadastre starts to rise rapidly in an asymptotic manner as the delivered heat approaches the total heat demand of the municipality. The growth with Hotmaps and Heat Roadmap Europe follows a similar pattern, but it starts later since these two projects expect a higher heat demand. Finally, the analysis of the results from the three datasets allows us to conclude that it would be highly likely to deliver 600-700 GWh with marginal costs below 30 €/MWh.

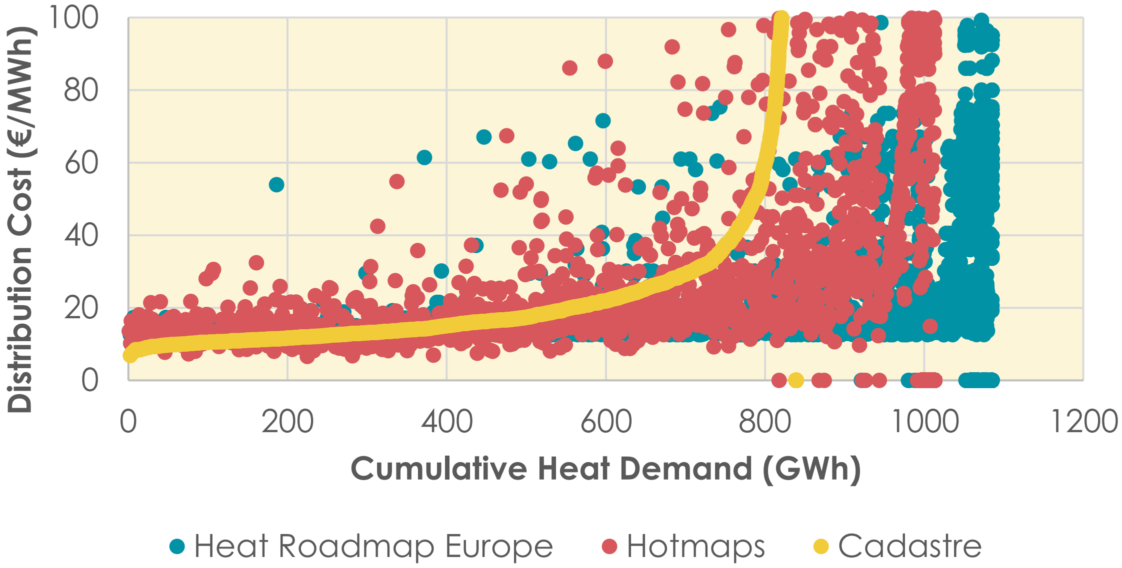

FIGURE 14. MARGINAL DISTRIBUTION COST SORTED BY THE CADASTRE DISTRIBUTION COST.

The analysis of the second figure, Figure 15, permits us to conclude that supplying 650 GWh would have an average cost in the range of 17-20 €/MWh. The lowest cost is provided by HRE, whereas Hotmaps indicates the upper bound, and the Cadastre delivers an average cost of 18 €/MWh, which will be used hereinafter.

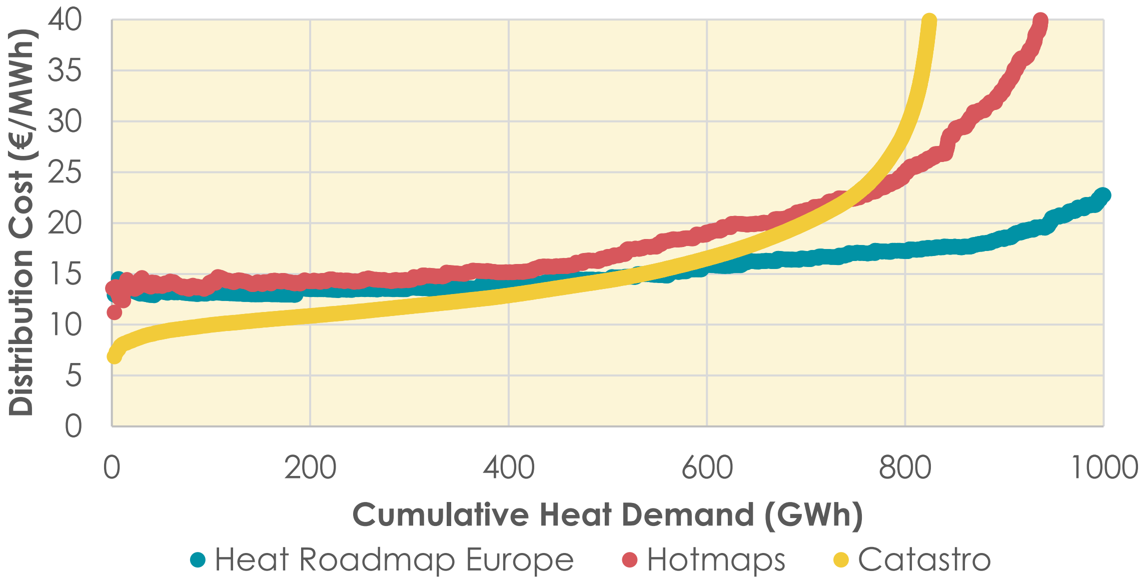

FIGURE 15. AVERAGE DISTRIBUTION COST SORTED BY THE CADASTRE DISTRIBUTION COST.

Finally, Figure 16 indicates the required investment to build a district heating network in the city of Bilbao with different expansion levels. At the wished level of 650 GWh, the required investment would rise to 174 million euros.

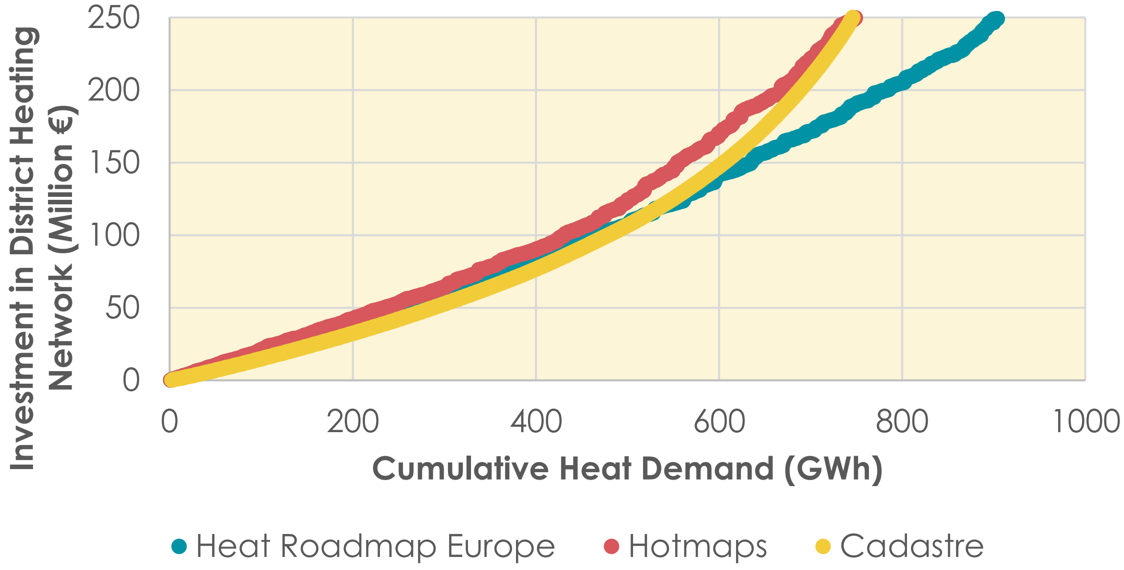

FIGURE 16. INVESTMENT IN DISTRICT HEATING NETWORK IN BILBAO.

2.3.1.4. Production

The overall principle for obtaining the best combination of production units has been to reduce carbon emissions as much as possible whilst maintaining the overall cost at a reasonable level. In order to reach this goal, waste heat has been prioritised. This has the ancillary benefit of improving the economic competitiveness of the industrial companies located around the city. Excess heat has been followed by heat pumps, and the peak load will be delivered by gas boilers that will also act as backup generation. It must be highlighted that the sizing of the different units has been achieved through a simple optimisation based on average CAPEX and OPEX. However, a more thorough sizing of the units using commercial software such as EnergyPRO or mathematical programming [10] should be carried out. Finally, most of the cost data employed in this study stem from the Danish Technology Catalogue [39], which provides standard costs of different production plants to be used in cost-benefit analysis. It must be noted that these costs are generally conservative when compared to first-hand experience in Danish projects. Furthermore, it would likely be feasible to obtain lower costs in Spain due to the significant difference in the labour costs[11] [40].

2.3.1.4.1. Heat Load

The heat load curve, which will be used in the different calculations, has been calculated as the sum of three components, the space heating demand, the domestic hot water demand, and the heat loss.

---

[10] As an example, Dorotić et al. proposed a multiobjective optimization for carbon emissions and cost based on linear programming. Furthermore, the reader may find an interesting review and comparison between EnergyPRO and mathematical programming in (Andersen and Østergaard, 2019). The Hotmaps dispatch model could also be used.

[11] As an example, unit labour costs in the construction sector are twice as high in Denmark.

According to the SPAHOUSEC study carried out by IDAE [41], the domestic hot water demand accounts for 52% of the heat demand in flats from the region of Northern Spain. The remaining 48% is used for space heating purposes. This distribution is nearly identical to the distribution provided by a more recent study on individual natural gas heating in the different climatic regions of Spain [42], and therefore, it will be assumed in this report.

The heat losses of the pipe network have been assumed to be 10% of the total heat demand. This figure is relatively conservative in relation to the levels found in Denmark. The average linear heat density of the system would be 13 GJ/m and 20 GJ/m depending on whether service pipes are considered or not, and experience from Danish networks shows that the expected heat loss for this level of linear heat density would range from 6% to 8%.

Concerning the temporal allocation, the space heating demand has been assumed to be proportional to the degree-days in the city with a threshold temperature of 15°C.

The yearly apportions of DHW and heat losses have been more straightforward, and they have been assumed to be constant over the year. Certainly, the heat losses vary sinusoidally over the year depending on the ground characteristics and the depth of the pipes, and the domestic hot water demand is bound to be lower in the summer due to higher temperatures of the water from the mains and lower consumption due to the urban exodus during the holiday season. An example of the variation of DHW over the year may be seen in Werner's study of Swedish District Heating Systems [43], which shows a 55% reduction in the summer load of DHW. However, due to time constraints, these refinements have not been considered, and it is deemed that they would not alter the results significantly.

All this information has been collected in Figure 17, which shows the total heat load and its three components.

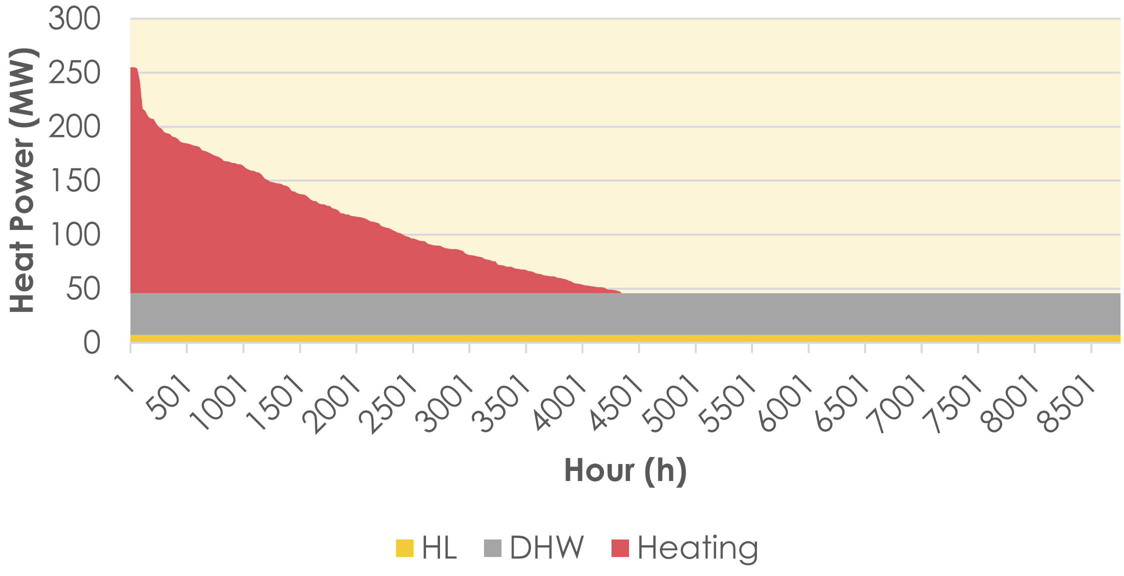

FIGURE 17. LOAD CURVE OVER THE YEAR IN THE CITY OF BILBAO FOR A HEAT DEMAND OF 650 GWH.

2.3.1.4.2. Excess Heat

In Table 2 it has been compiled the different sources of waste heat in the city's surroundings. The primary source is the Petronor refinery, followed by the Wastewater Treatment Plant of Galindo, both visible on the map in Figure 9. The Incineration Plant of Zabalgarbi (likewise visible in Figure 9) and the cement factory of Rezola Arrigorriaga represent the two smallest sources. It must be highlighted that the data provided by sEEnergies regarding the excess heat potentials is more realistic than the data provided by Heat Roadmap Europe, and the figures from the former will be taken whenever possible.

Aside from these facilities, it is possible that the generation of green hydrogen could represent a new cheap source of waste heat in the city's neighbourhood. The hydrolysis of water has an efficiency ranging from 50% to 80% [44], resulting in significant amounts of waste heat, which could be used for a district heating system. The city could also take advantage of the exhaust air from the metro system as the ReUseHeat Project has studied and the London Underground implemented [45].

TABLE 2. POSSIBLE WASTE HEAT SOURCES ACCORDING TO HEAT ROADMAP EUROPE AND SEENERGIES.

Information Source	Heat Source	Heat	Heat	Distance to town
(-)	(-)	(PJ)	(GWh)	(km)
HRE	CEMENTOS REZOLA ARRIGORRIAGA	0,75	208	9
HRE	ZABALGARBI, S.A.	0,45	125	6
HRE	EDAR GALINDO	2,47	686	7
HRE	PETRONOR	15,76	4378	17
sEEnergies	PETRONOR	1,218	338	17

The heat production from the wastewater treatment plant will be analysed in the next chapter as it requires the utilisation of a heat pump to raise the temperatures to a usable level. However, in the other sources, it is assumed that the heat will have a temperature high enough (70°C - 80°C) for direct use, and hence, there will be no need for heat pumps.

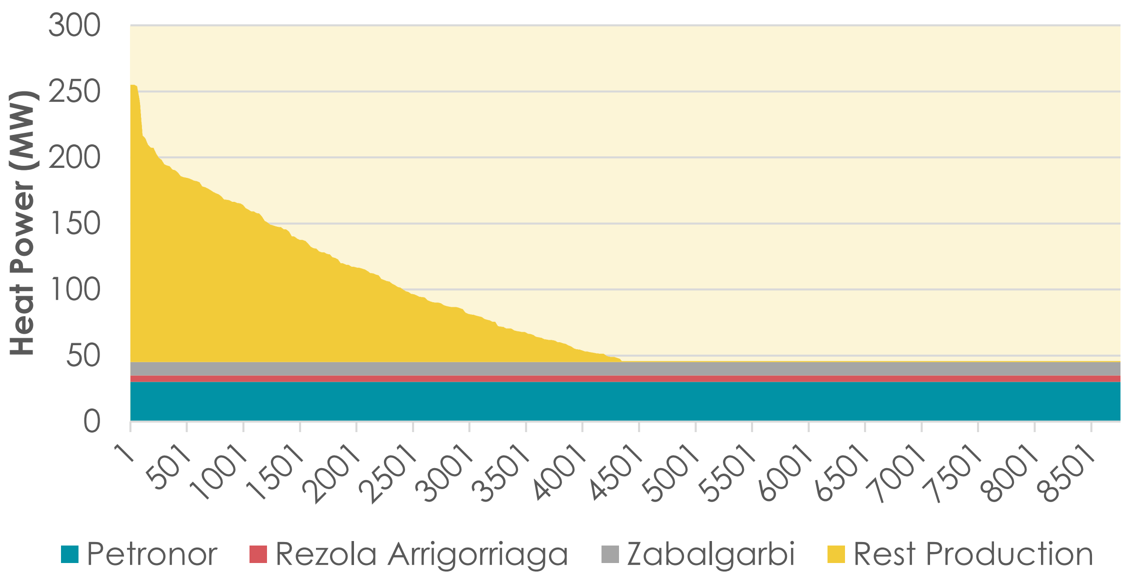

FIGURE 18. EXCESS HEAT PRODUCTION FROM DIRECT-USE SOURCES IN BILBAO.

If it is assumed that the heat delivery from these plants would be approximately constant over the year, it would be possible to arrive at the load curves depicted in Figure 18. Moreover, the heat power that each of the plants would provide, along with the maximum amount of heat delivered, have been collected in Table 3. In total, waste heat from direct use could cover 55% of the city's heat demand.

TABLE 3. SUMMARY OF WASTE HEAT PRODUCTION.

Heat Unit	Annual Energy (GWh)	Possible Maximum Heat Power (MW)	Maximum Heat Power (MW)	Actual Energy (GWh)
Petronor	300	34,2	30,0	262,8
Rezola Arrigorriaga	50	5,7	5,0	43,8
Zabalgarbi	100	11,4	10,0	87,6

The district heating system would need to pay a price high enough to allow the industrial companies to recover the necessary investments to capture the available excess heat and transfer it to the systems. At the same time, the sum of this price and the cost of transporting the heat to the city should be lower than the marginal cost of producing heat at the district heating company's units.

Unfortunately, there is a lack of literature showing the process and cost of reutilising industrial waste heat to District Heating systems, and the only detailed reference found is the case of Aalborg Portland, explained in [46]. In 1992 an investment of 82,5 million DKK allowed recovering 42 MW of waste heat to the district heating system of the city of Aalborg. Nowadays, the cement plant continues to supply heat to the city, accounting for approximately one-fifth of the city's heat demand. An update of these costs using the Danish Consumer Price Index would result in an investment of 500.000 €/MW. This figure will be used in this report, but it should be remembered that it is highly uncertain.

The industrial partners would likely demand a low payback period to recover their investments since these are out of their business core. Thus, a payback period of three years will be assumed. Given the amounts of heat sold to the DH system, the payback period constraint, and the assumed investment cost, the heat price should be at least 17 €/MWh.

2.3.1.4.3. Other sources

The waste heat sources would cover the system's baseload, supplying 55% of the heat demand. The rest should be provided by other units installed by the district heating system. There is a wide range of possible heat sources that the system could use, but due to time constraints, the set of possible options will be kept at a reasonable level, and it is summarised below:

- Heat Pump using the wastewater treatment plant as the heat source.
- Heat Pump using the sea as the heat source.
- Biomass Heat-only-boiler.
- Natural Gas Cogeneration plant.
- Natural Gas Boiler.

The heat pumps would deliver the highest degree of decarbonisation at present and in the future. The current emission factor of electricity in Spain is relatively low, with 220 Kg/MWh, and it is expected to fall in the future as the decarbonisation of the electricity sector progresses. Due to the efficiency of the heat pumps, their emission factor would be even lower. The emissions from a biomass boiler would depend on the time frame since the combustion of biomass emits a considerable amount of greenhouse gasses, but they may be removed with the future growth of the vegetation. Therefore, in this analysis, they will be assumed to be null. From an environmental standpoint, the natural gas options would be the worst, but they also present lower investment costs.

Table 4 and Table 5 have compiled the different parameters utilised for the sizing of the different production units. The primary source for these two tables is the Danish Technology Catalogue elaborated by the Danish Energy Agency [39], but additional sources are indicated in the comments after the tables.

TABLE 4. PRODUCTION UNITS ECONOMIC AND ENVIRONMENTAL PARAMETERS (1 OF 2).

Unit	Investment Cost	O&M Fixed	O&M Variable	Efficiency
	€/MW	€/MW	€/MWh	(-)
Natural Gas Boiler	60.000	2.000	1,1	105%[IV]
Heat Pump	382.183[I]	2.000	3,3	303%[II]
Biomass Boiler	680.000	32.800	1	115%[IV]
Natural Gas Engine	1.000.000	10.000	5,4	50%[III]

TABLE 5. PRODUCTION UNITS ECONOMIC AND ENVIRONMENTAL PARAMETERS (2 OF 2).

Unit	Price Fuel	CO_2 tax	CO_2 Emission	CO2 price	Total Fuel Cost	Marginal Heat Price
	€/MWh	€/ton	ton/MWh$_{fuel}$	€/MWh	€/MWh	€/MWh
Natural Gas Boiler	28,43[V]	150 (50) [VIII]	0,24[X]	27 (9)	64,4 (40,4)	62,5 (39,6)
Heat Pump	72,87[VI]	0 [IX]	0,22[XI]	0	72,9	27,4
Biomass Boiler	25 [VII]	0	0,42[X]	0	25,0	22,7
Natural Gas Engine	28,43 [V]	150 (50)	0,24[X]	27 (9)	64,4 (40,4)	83,9 (36)[XII]

I. The Danish Energy Agency indicates a unit investment cost of 480.000 €/MW for a sea-water plant of 20 MW, and it also points out a price elasticity of 0,8 with size. This price corresponds to a unit of 62,5 MW. It must be noted that the unit cost suggested by [47] for a 10 MW heat pump in a feasibility study in Asturias was considerably lower (200.000 €/MW), and this price tag is proportionally higher than the budgeted cost of 300.000 €/MW for a 2 MW heat pump installed in the District Heating system of Mieres in Asturias[12] [48].

II. The COP for the heat pumps has been calculated assuming District Heating System Temperatures of 50°C and 80°C, an inlet temperature to the evaporator of 13°C and an outlet temperature of 5°C and a Lorentz efficiency of 50%, coherent with Danish experiences [49].

III. This efficiency refers to the heat efficiency. The electricity efficiency has been assumed to be 45%, according to the Technology Catalogue.

IV. Condensation of the water vapour is assumed in order to increase the efficiency.

[12] This price includes the proper execution cost ("*Presupuesto de Ejecución Material*") and the usual profit margin and overhead (6% and 13% respectively).

V. The natural gas price has been taken from Eurostat's database [40], which provides the average natural gas prices for industrial consumers with different consumption levels. The average price during the period 2015-2020 from the range 100.000-1.000.000 GJ has been chosen.

VI. The average electricity price during the period 2015-2020 for industrial consumers in the consumption band 70.000 – 150.000 MWh has been taken. However, given the structure of the Spanish electricity rates, with varying network fees depending on the period and the high weight of fixed non-energy fees, this price is merely an approximation.

VII. The biomass price has been taken from IDAE's annual report on biomass prices, assuming that the biomass source would be wood chips.

VIII. A carbon tax of 150 €/ton has been considered for the two natural-gas-based sources. However, since this value is considerably higher than the current carbon price in the market, the resulting costs, and prices of applying a lower carbon tax of 50 €/ton are also provided.

IX. The cost of carbon should be incorporated into the electricity price.

X. The emission factors of natural gas and biomass have been taken from the JRC report to the Covenant of Mayors [50]. They are similar to those proposed by the Spanish Central Government [51].

XI. Average emission in the period 2015-2020 according to the Spanish TSO, *Red Eléctrica* [52].

XII. The price of heat for a natural gas engine considers the income from selling electricity in the spot market at a price of 50 €/MWh and an electrical efficiency of 45%.

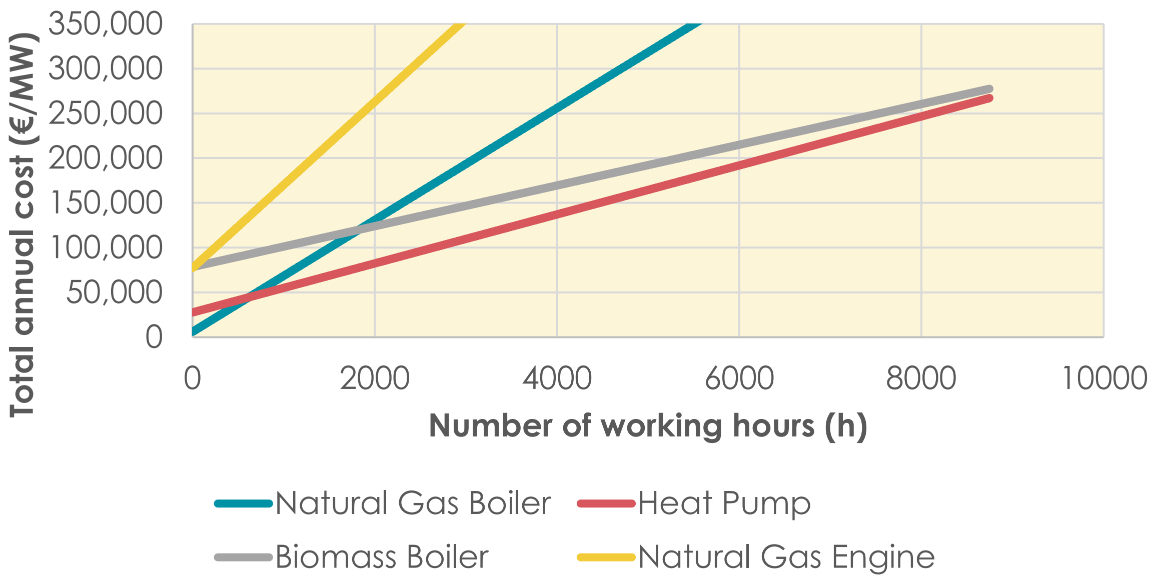

FIGURE 19. TOTAL ANNUAL COST OF USING A UNIT DURING A CERTAIN NUMBER OF HOURS AND A CARBON PRICE OF 150 €/TON.

Using this information, it is possible to obtain the total annual cost of running the different units during different periods and determine which units are best suited as baseload or peak load. In Figure 19, it has been depicted these results, and it becomes clear that generally, the most economical unit is the heat pump except for peak-load when a natural gas boiler is much cheaper due to its very low CAPEX. Were the carbon tax to be lower (50 €/ton), the natural gas boiler would be the cheapest option for a longer number of hours, but the overall picture would not change drastically.

Taking into account these costs, the units presented in Table 6 are proposed. It must be noted that the high heat power of the natural gas boilers not only accounts for the necessary peak load demand but also as backup in case of failure or maintenance of the other units. This causes a very high average heat price from these units. Something similar happens to the sea heat pump as this unit has a low capacity factor (16% or 1400 hours), and the investment cost needs to be allocated in a small heat production.

TABLE 6. HEAT PRODUCTION UNITS FOR BILBAO

Unit	Heat Power (MW)	Heat Production (GWh)	Investment (M€)	Fixed heat price[13] (€/MWh)	Marginal heat price (€/MWh)	Total heat price (€/MWh)
Natural Gas Boiler	255	22	15,3	70	62,5	133
Galindo Heat Pump	75	231	28,7	9	27,4	36
Sea Heat Pump	50	68	19,1	20	27,4	47

The units here proposed would be able to deliver the heat demand presented in Figure 20.

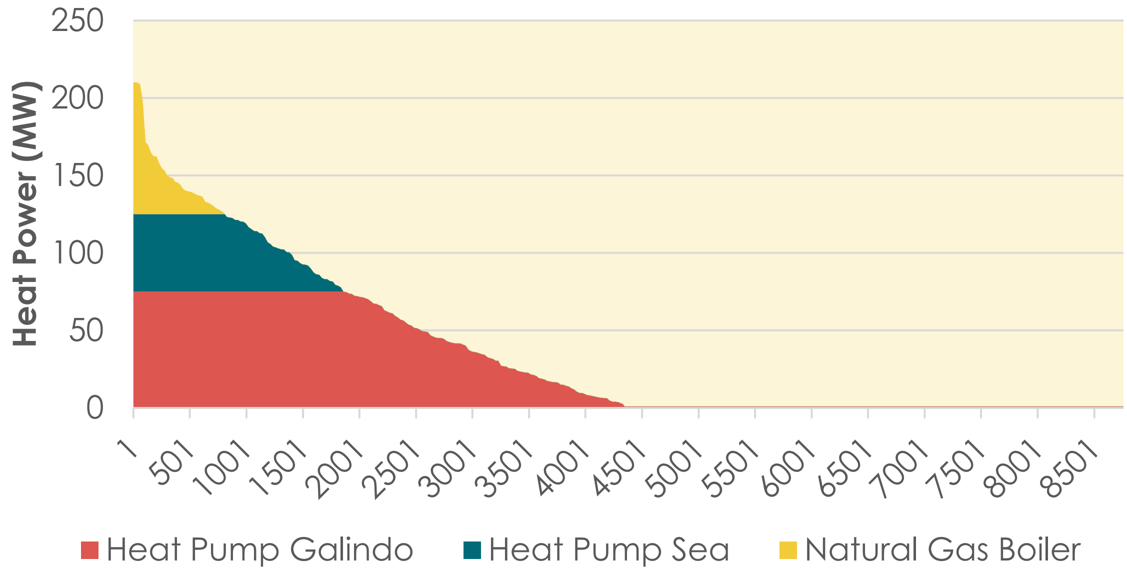

FIGURE 20. HEAT LOAD FROM HEAT PUMPS AND NATURAL GAS BOILERS.

[13] This "fixed heat price" is calculated as the total fixed cost (CAPEX + non-production dependent OPEX) divided by the total heat production.

2.3.1.4.4. Storage

Thermal heat storage is an essential element of district heating systems as it enables the decoupling of heat production and consumption, leading to a reduction of the variable production costs. Furthermore, they also ease disruptions of the heat supply from the various production units. An example of the utilisation of storage and dispatch of the different production units to minimise the marginal cost is shown in the production of the District Heating System of Skagen in Denmark in Figure 21. It can be appreciated that during the 23rd of May, the heat pumps were producing heat and loading the storage while the prices were low (-150 to 450 DKK/MWh or -20 to 60 €/MWh[14]), and they came to a halt when the spot prices suddenly rose. In these hours, the production from the Combined Heat and Power units was started, which was also motivated by the high prices (circa 1050 DKK/MWh) in the regulation market[15].

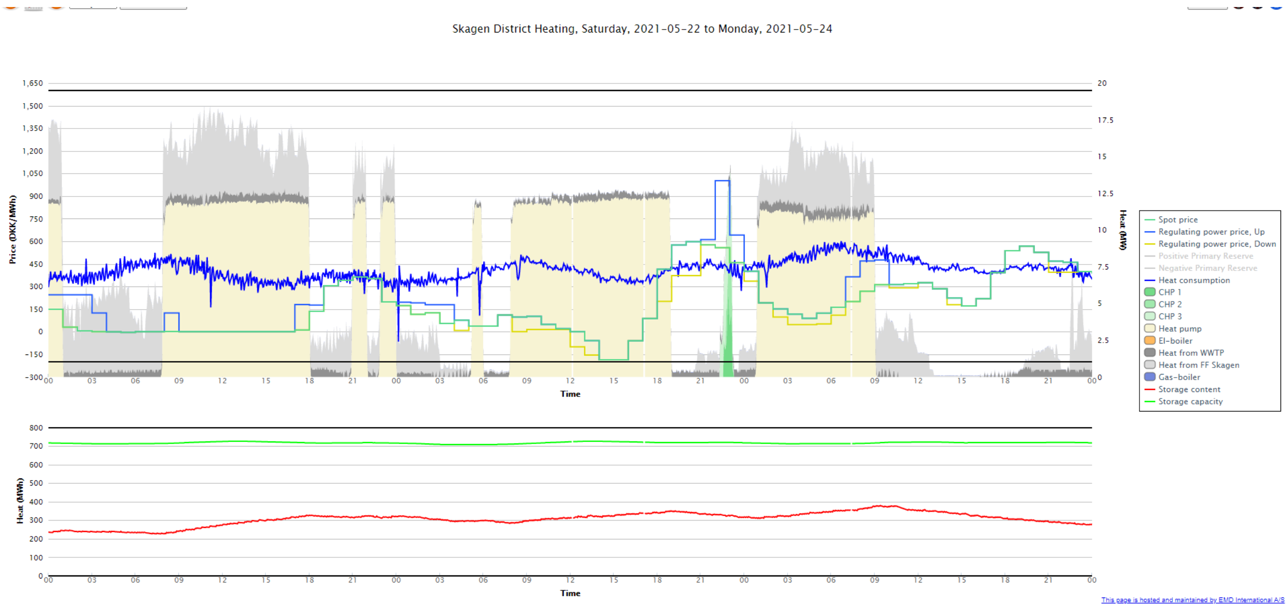

FIGURE 21. HEAT PRODUCTION IN THE DISTRICT HEATING SYSTEM OF SKAGEN (DENMARK). SOURCE: [53]

The optimal size should result from a more detailed analysis, but here the average storage capacity of District Heating Systems in Northern Europe will be considered. According to Werner and Gadd [54], District Heating systems in Scandinavia have an average heat storage capacity of 10 m^3/TJ, which in the case of Bilbao would result in a size of 23.400 m^3.

A non-pressurised Thermal Storage Tank of 24.000 m^3 would have an approximate unit cost of 155 €/m^3 [54], leading to a total investment cost of 3,7 million euros. It must be noted that this unit cost is more than twice as high as that reported by the Danish Technology Catalogue (65 €/m^3) [55].

2.3.1.4.5. Transmission Pipes

The heat from the different production units must be transported to the city of Bilbao. In order to reduce the cost, the transmission lines will be shared between different production units whenever possible. They can be divided into three pipelines:

[14] Negative spot prices do occur occasionally in the Danish Spot Market.
[15] Primary regulation is auctioned in Denmark.

- Y transmission pipeline: this pipeline has a common stretch between the city centre and the Wastewater Treatment Plant of Galindo, after which two different branches continue towards the refinery of Petronor and the port, where the sea heat pump could be installed.
- Pipeline to the incineration plant of Zabalgarbi.
- Pipeline to the cement factory of Rezola Arrigorriaga.

In Table 7 below, it has been summarised the different pipelines, their approximate distance, the heat they should transport, the required flow, pipe diameter and investment cost. In these calculations, it has been assumed a temperature difference of 40°C and an optimum speed of 1,8 m/s. In reality, this speed and diameters are only a first-order approximation, and a detailed analysis of the hydraulics should be carried out bearing in mind the topography of the terrain, the location of the pumping stations and the pressurisation unit. The pipe installation costs have been taken from the updated to 2020 Swedish Pipe Catalogue in green areas [31, 32]. The total cost of this transmission network would be 75 million euros, which would translate to 7,3 € for each transported MWh. The heat losses and the pressure losses would barely increase this cost, and in this study, they will be neglected.

TABLE 7. TRANSMISSION PIPELINES BETWEEN WASTE HEAT PRODUCTION UNITS AND THE CITY OF BILBAO.

Pipeline	Approximate distance	Total Heat Power Transported	Flow	Pipe Diameter (DN)	Unit Cost	Investment Cost
	(Km)	(MW)	(m^3/s)	(mm)	(€/m)	(M€)
Galindo to Centre	9	155	0,93	800	2.841	24,9
Sea to Galindo	11	50	0,30	450	1.703	19,2
Petronor to Galindo	13	30	0,18	350	1.378	17,2
Rezola Arrigorriaga	11	5	0,03	125	647	7,3
Zabalgarbi	8	10	0,06	200	890	6,7

2.3.1.4.6. Summary Production

In Figure 22 it has been depicted the load from all the production units. In addition, below is shown a summary of the system's necessary investments and running costs.

- Total investment: 142 M€
  - Transmission pipelines: 75 M€
  - Heat Pumps: 47 M€
  - Gas Boilers: 15 M€
  - Storage: 4 M€
- Unit investment cost: 14,7 €/MWh
- Fixed O&M: 1 M€
- Unit investment cost and O&M: 16 €/MWh
- Marginal cost of heat supply: 23 €/MWh

- Marginal cost of heat supply at the consumers taking into account heat losses: 25 €/MWh
- Total cost of heat supply: 41 €/MWh

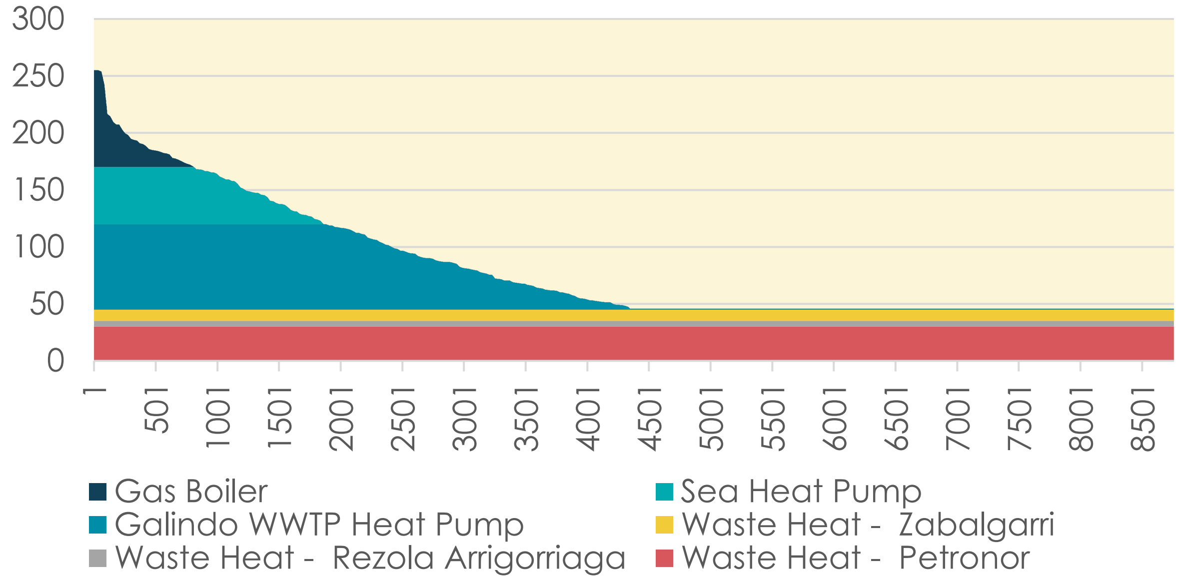

FIGURE 22. HEAT LOAD FROM ALL PRODUCTION UNITS (MW).

2.3.1.5. Connection to consumers

Most of the dwellings of Bilbao are currently supplied by individual natural gas boilers, whose conversion to district heating is bound to be the most challenging. Therefore, the system ought to aim for the most cost-effective and straightforward solution.

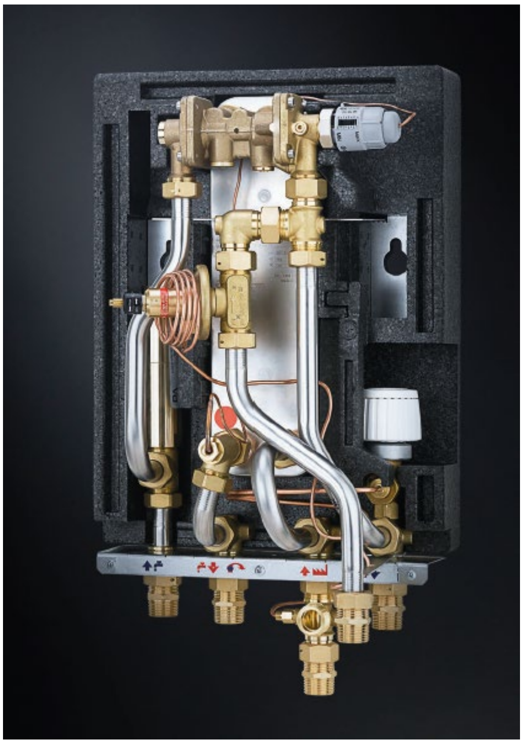

FIGURE 23. DISTRICT HEATING SUBSTATION DANFOSS REDAN AKVA LUX II TDV. SOURCE: DANFOSS

The simplest type of substation is a unit such as that shown in Figure 23. It has an instantaneous preparation of domestic hot water by means of a plate heat exchange, which eliminates the need for water storage and a direct connection to the heating system. The lack of water storage minimises the risk of legionella proliferation whilst delivering a low return temperature (10-25°C). Moreover, the direct connection not only is less prone to errors in the control system since it only requires a pressure difference controller but also it is a considerably cheaper solution due to the lack of a pump, expansion tank and a more complicated control system.

This type of substation is the most common in Denmark due to its simplicity and cost, but it also comes with the disadvantage of imposing lower pressures in the district heating network. For instance, in this country, the pressure in the distribution system is usually limited to six or ten bars, and higher pressures are only utilised in the transmission system. The price of these units to the public is around 1000 € - 1200 €[16], so it is deemed feasible to obtain a lower price, were the district heating system to acquire them in bulk from the manufacturer. Therefore, it will be assumed that they have a cost of 750 €.

The cost of the heat meter is assumed to be 250 €.

The installation of the pipe risers to each flat is more difficult to ascertain, but the recent experience of the SmartENCity project in Vitoria sheds some light on this issue. The analysis of the budget for the connection of the building located in *Eulogio Serdán 8* [56] suggests a construction cost of 1300 €/apartment. If the usual 6% profit margin and 13% overhead is added, the installation cost would rise to 1400 €/apartment.

Given that no control system is provided at the substation, it needs to be installed at each heat emitter. Thermostatic valves with pre-setting are ideal for this task since they enable the radiator simultaneously to deliver the necessary heat output and the lowest possible return temperature. If it is assumed that, on average, a flat would require 8 TRVs with a unit cost of 40 €, which would result in a total cost of 320 €. The sum of the different elements enumerated in this section would amount to 2.720 €. Applying the same annuity as before, the annual cost would then be 183 €. Considering that the average heat demand per dwelling is 5 MWh per year [42], the unit cost rises to 37 €/MWh.

2.3.2. *Cost of alternative sources*

2.3.2.1. Electricity

In this section it will be assessed the cost of an alternative heat supply by means of two electric options:

- All joule: in which an electric water tank provides the domestic hot water and the heating is supplied by electric radiators.
- Heat Pump: An Air-to-air heat pump for the heating supply and an air-to-water heat pump for the DHW preparation[17].

[16] These units are rare to the Spanish consumer, but they can be easily found in Danish websites:
https://vvsproffen.dk/shop/vvs-varme-fjernvarme-units-tilbehoer-fjernvarme-units-375076041-19184p.html
https://www.vvs-shoppen.dk/redan/redan-akva-lux-ii-tdv-fjernvarmeunit-fuldisoleret-med-ave/
https://www.wattoo.dk/danfoss-redan-akva-lux-ii-tdv-akva-lux-ii-tdv-fjernvarmeunit-xb06h-1-26-m-ave-til-direkte-anlaeg-375076053-1

[17] A solution with a Joule water tank has also been studied and the resulting cost is similar although the share of investment and running costs is rather different.

2.3.2.1.1. Prices of electricity

The hourly averages of electricity prices have been calculated for the period ranging from April/2014 to March/2021 and are shown in Figure 24. The starting point of these prices is the regulated rate "PVPC" [52], which is indexed to the spot market, to which the new network fees [57] have been applied retroactively. The average off-peak price (0-8 h) in the period has been 75 €/MWh, whereas, in the rest of the hours, the mean price has been 142 €/MWh. Moreover, the current peak cost of power is 37 €/kW·year, including the electricity tax.

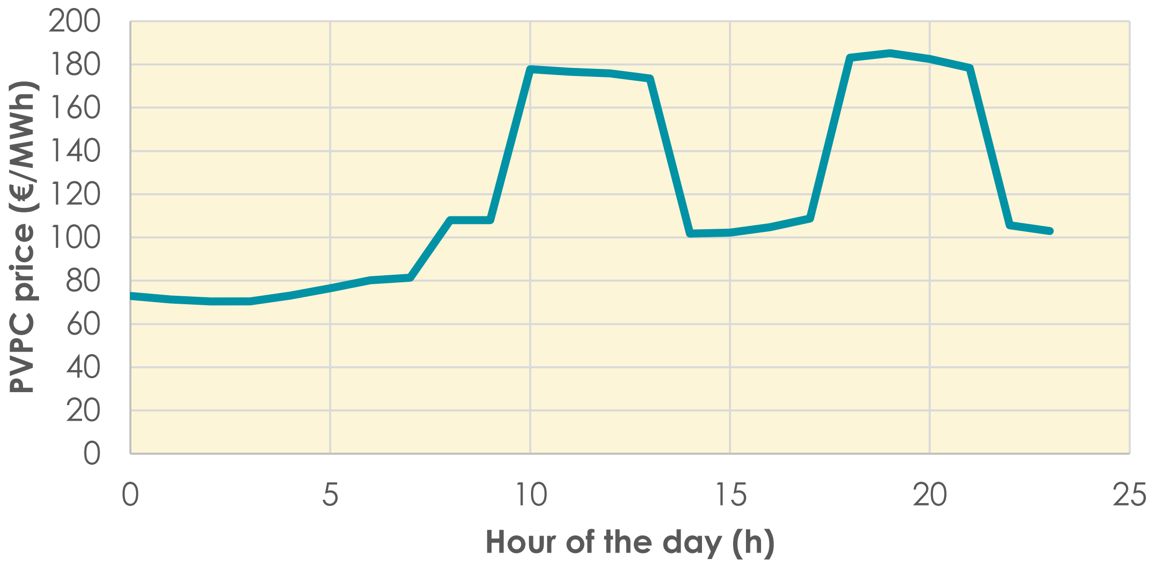

FIGURE 24. AVERAGE HOURLY PVPC PRICES WITH THE NEW NETWORK FEES[18] [19].

Massive electrification of the heat demand would likely make the spot price more sensitive to the heat demand, as the recent Filomena Storm highlighted, but this possible increase will be neglected in this study.

2.3.2.1.2. All Joule Heating

As has been mentioned before, recent studies of the heat demand have shown that the total heat demand is divided evenly between space heating and domestic hot water. Therefore, if it is assumed that the domestic hot water tank only functions during the off-peak period thanks to a programmer and the space heating is consumed uniformly between 8h to 24h, the resulting average price for heat would be 121 €/MWh.

Besides the marginal cost of the heat supply, the electrification of the heat demand would require an increase in the power required by the dwelling. Assuming a conservative 50 W/m^2 and an average dwelling size of 80 m^2, the dwelling would require 4 kW extra with an annual cost of 150 €. The investment cost for Joule heating may be assumed to be 500 €. Assuming a lifespan of 20 years, the same interest rate, 3%, and a heat demand of 5 MWh/year, the resulting cost would merely be 7 €/MWh, which is neglectable compared to the running costs or the investment costs of the other solutions. The total cost of this solution would rise to 141 €/MWh.

[18] These prices include the Electricity tax (5%) but exclude the VAT.
[19] These prices take into consideration the difference in network fees between weekdays and weekends.

2.3.2.1.3. Heat Pump

The most expensive part of the heat supply with the All-Joule heating option is the running cost, especially for space heating, which is consumed mainly during peak hours. Moreover, each dwelling must raise the maximum power the dwelling is allowed to consume compared to a non-electrified heating system. Hence, the substitution of joule space heating with an air-to-air heat pump and the utilisation of an independent air-to-water heat pump for Domestic Hot Water preparation could bring about significant reductions in the operation cost at the expense of higher investment costs.

If the space heating heat pump is assumed to have a COP of 4,5 [58], the heat price for space heating would fall from 142 €/MWh to 32 €/MWh. On the other hand, bearing in mind that the COP for an air-to-water DHW heat pump is around 2, the heat price for the DHW would be 37,5 €/MWh. Therefore, the average marginal cost of this solution would be 35 €/MWh. In this case, the extra cost for the maximum power is much smaller, thanks to the efficiency of the heat pumps. As a result, only some additional 900 W would be required, translating into a cost of 35 € per year or 7 €/MWh.

The investment cost for the single air-to-water heat pump unit may be assumed to be 1000 €[20], although [59] suggests higher prices in the range 2000-3000 €. Regarding the air-to-air heat pump, the easiest technology to install is a single split or multi-split system, which consists of one external unit where the evaporator is located and several units inside the premises to be heated. However, the cost is highly variable, and the Spanish database from CYPE [59] suggests prices ranging from 1500 € to more than 3000 € depending on the number of units and equipment quality. Furthermore, anecdotal evidence suggests that a price as low as 1000 € for a 1x1 system would be possible. Given this uncertainty, it has been assumed three price levels, 1000 €, 2000 € and 3000 € which would account for a cheap, medium and an expensive alternative. Assuming an amortisation of 12 years, the investment cost would be 40 €/MWh, 60 €/MWh and 80 €/MWh for the three alternatives.

2.3.2.2. Natural Gas

Natural Gas represents the main source for space heating and Domestic Hot Water preparation nowadays. Therefore, all the possible solutions should be compared to it in order to assess whether the economic incentive to shift towards low-carbon solutions is high enough, or public support is needed. During the last two decades, the prices for Natural Gas have been rather stable in real terms, as can be appreciated in Figure 25. The average price in the last decade (2010-2021) has been 71 €/MWh for a consumption level of 5 MWh. As it can be seen, the price for lower consumption levels is higher, and it would be lower for higher annual consumptions as the fixed fee would account for a lower proportion. Assuming an efficiency of 90% for the boiler, the heat price would be 79 €/MWh. To this energy price, it is likely that in the future, two other components are added:

- Carbon tax: a 100 €/ton carbon tax would translate into an additional cost of 24 €/MWh. If implemented, it would likely occur at a European level as it seems extremely far-fetched that a carbon tax, even with a full rebate as it has been implemented in Canada at a federal level, could be introduced in the current political environment.

[20] Sources: different Spanish websites including Leroy Merlin.

- "*Fondo Nacional para la sostenibilidad del sistema eléctrico*". This fund in preparation would apportion the cost of promoting renewable sources in the electricity sector to the entire energy mix. It is still under legislative development, and hence, its implementation is uncertain. However, were it to be fully rolled out, the market regulator ("*Comisión Nacional de los Mercados y la Competencia*" or CNMC in short) has studied that it would have an impact of 5 €/MWh for domestic consumers [60].

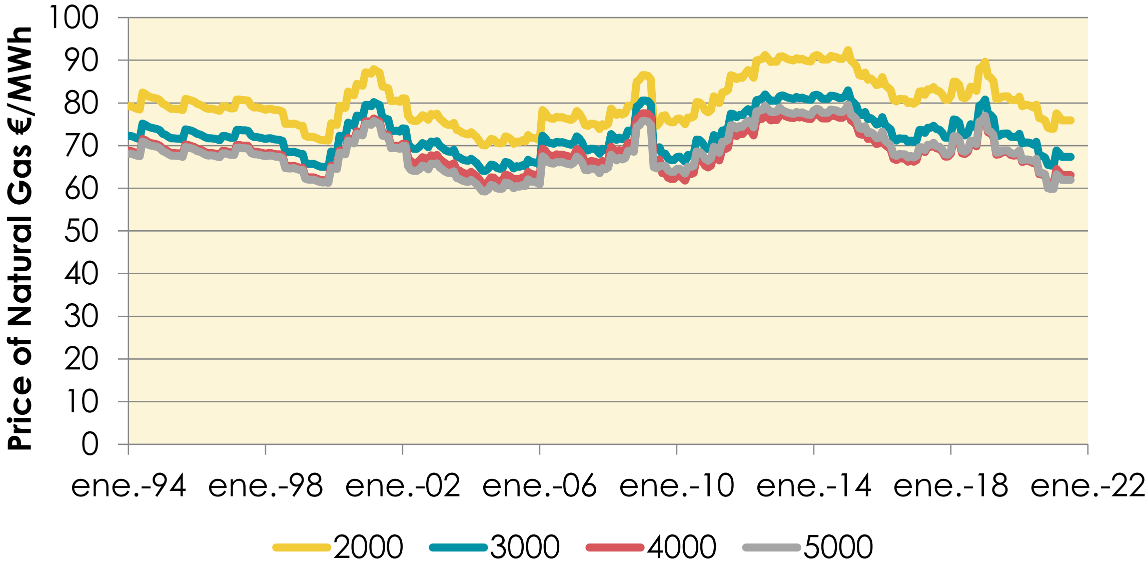

FIGURE 25. REGULATED PRICES OF NATURAL GAS IN SPAIN[21]. SOURCE: [61, 62]

The total heat supply cost is the result of the sum of the marginal supply cost and the annualised investment costs. However, when it comes to natural gas boilers, it could be argued that the latter are sunk costs, and hence they should not be considered. In order to leave the option for the reader to decide their impact, they will be indicated separately. A natural gas boiler may cost 1.400 € and have a lifespan of 15 years. With these conditions, the annualised cost would amount to 117 € and the specific cost 23 €/MWh.

2.3.3. Economic comparison with alternative sources

In Figure 26, it has been summarised the cost of the different heating solutions analysed in this study. In this bar graph, it has been depicted the different components in order to allow the reader their assessment as it was indicated before with the natural gas boiler.

An examination of the chart allows us to draw the conclusion that Joule heating is the most expensive solution due to the high price of electricity and its low efficiency. Moreover, natural gas is the second most expensive option, provided that some form of carbon pricing is implemented. Otherwise, this energy source would be the most competitive heating solution, especially if the investment costs are disregarded. The two low-carbon solutions, the district heating system, and the heat pump option, would have similar costs, although the exact competitiveness of the heat pump is rather sensitive to the installation cost of the units. Thus, the heat pump option could be either cheaper or more expensive than district heating, although, in the lower end, it would not be possible to warm up the entire dwelling.

[21] The prices include the Natural Gas Tax of 0,65 €/GJ but exclude the VAT. The prices reflect the average price pay at the different consumption levels and they result from the sum of the marginal tax and the prorated fixed fee.

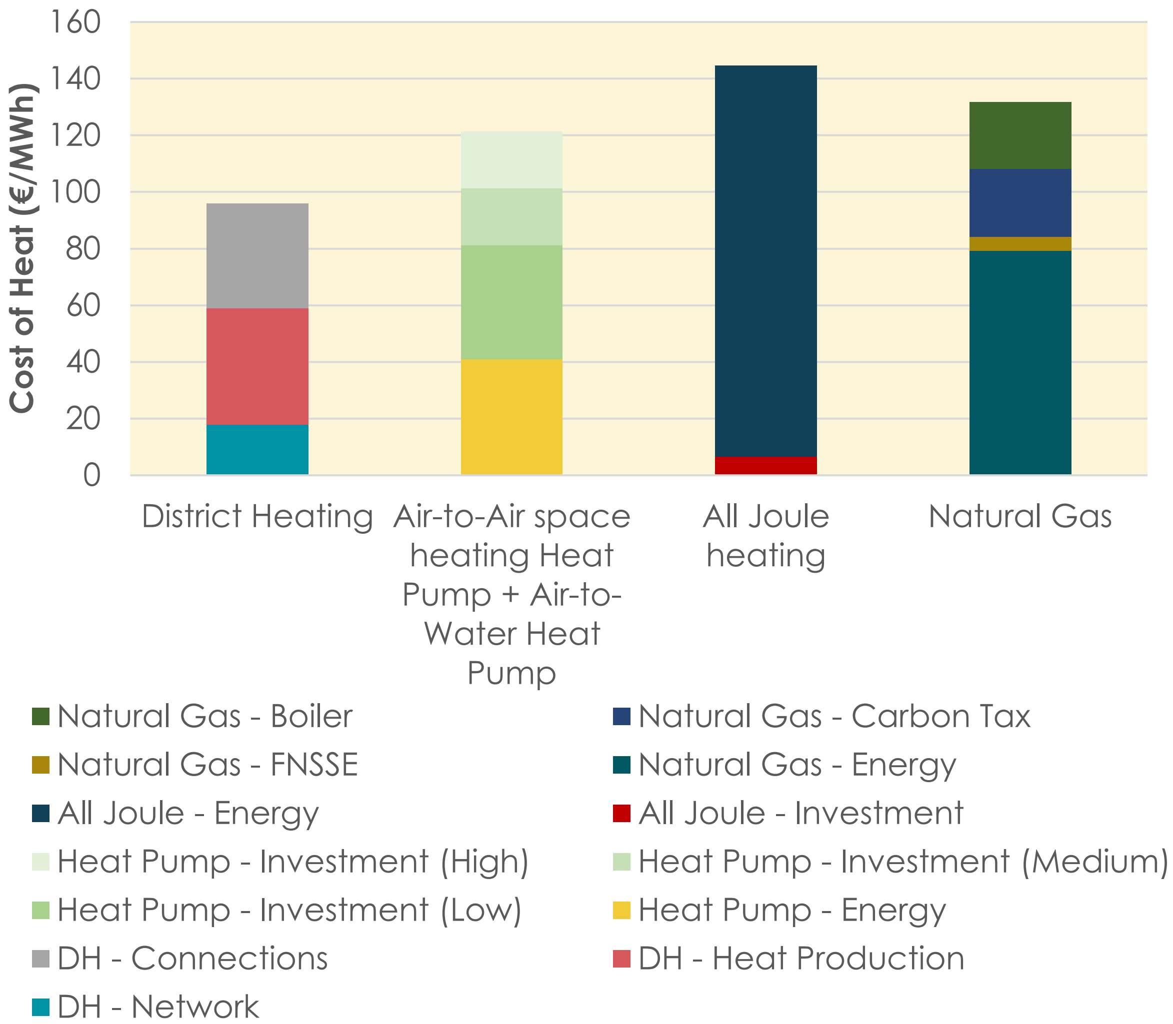

FIGURE 26. COST OF DIFFERENT OPTIONS OF HEAT SUPPLY FOR A HEAT DEMAND OF 5 MWH.

The previous comparison shows that District Heating could be a feasible option for the city of Bilbao despite its mild climate. The high heat demand density of the city, due to the very high population density, leads to a meagre specific cost for the district network. Moreover, the industries located in the surroundings of the city could provide low-cost heat. Nonetheless, the lack of significant energy or carbon taxes on natural gas could jeopardise the development of a district heating system. Therefore, a combination of regulatory and/or economic incentives would have to play a considerable role. For example, a carbon tax with a rebate, such as Canada's [35, 36], may be worth exploring. This scheme consists of a carbon tax whose income is returned entirely to the citizens as a dividend. It is revenue-neutral, and it could have an interesting redistributive impact. For instance, were the city to impose a carbon tax of 100 €/ton, the city could raise 13,44 million per annum, which would translate into a check of 38 €/person·year[22].

2.3.4. Carbon emissions

The district heating system's supply may be grouped into three categories: industrial waste heat, heat pumps, and natural gas, whose relative shares are indicated in Figure 27.

[22] It has been assumed a natural gas demand of 560 GWh, a carbon emission factor of 0,24 ton/MWh and a population of 350.184 inhabitants in 2020 according to the *Instituto Nacional de Estadística*.

On condition that the carbon emission factor of waste heat is assumed negligible since this heat would otherwise not be employed, the carbon emission factor of district heating would be 41 Kg/MWh_{heat}. Given that Natural Gas has an emission factor of 267 Kg/MWh_{heat}[23], a district heating supply would bring about an 85% reduction of the greenhouse emissions from the city's heating supply. A heat pump could achieve a carbon emission factor of 79 Kg/MWh_{heat} with the current average electricity mix, which is similar, although somewhat higher than the heat pump option.

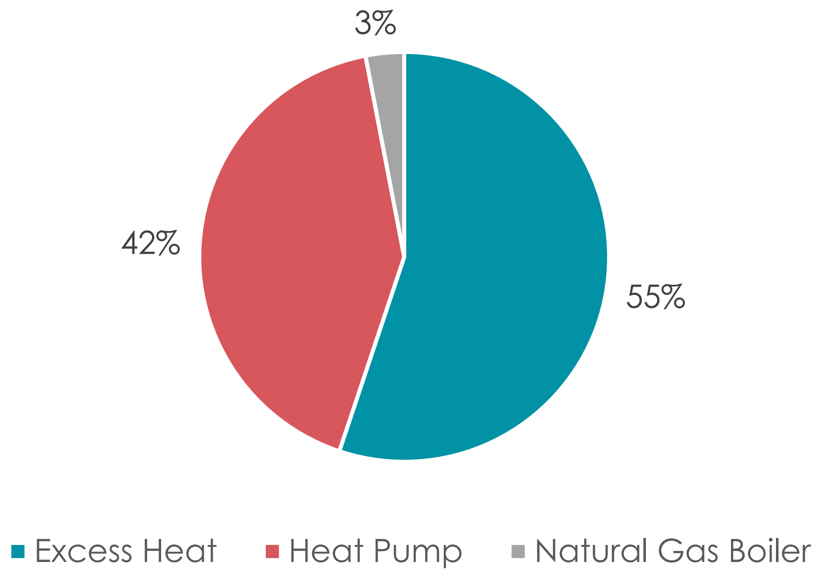

FIGURE 27. SHARE OF HEAT SOURCES IN THE DISTRICT HEATING SYSTEM.

2.3.5. *Progressive expansion*

This study has shown how a district heating system could supply almost the entire city. However, although technically possible, it would likely not be very realistic to expect a complete roll-out of the system in a short period of time. The entire network could take a decade to be implemented.

A more realistic approach would consist of a steady expansion of the network from the most suitable areas into the less suitable areas. The most suitable areas would be those with large customers and public buildings which would serve as anchor loads, areas with high heat densities and more affluent neighbourhoods. These areas should be prioritised as they would be the most profitable for the company and ensure the enterprise's long-term success. As an example of a progressive expansion of a District Heating System, Magnusson [63] shows the evolution of Stockholm's District Heating System over a period of three decades.

Concerning the production units, a good starting solution could consist of natural gas boilers since these have low investment costs. Once a certain head demand has been reached, it would become feasible to connect the system to the industrial waste heat plants. The two best located are the cement factory and the incineration plant due to the shorter pipelines. Only after the district heating system has expanded sufficiently, it would become feasible to develop the refinery and heat pump sources.

[23] An efficiency of 90% has also been taken for this figure.

The consumers would represent the most significant challenge as there exists a negligible knowledge of District Heating in Spain, and the population is not very accustomed to communal solutions. Furthermore, the recent experience from Vitoria highlights that the immense majority of individual consumers would not see a clear benefit in abandoning natural gas for a novel heat supply solution such as district heating.

A carrot and stick approach could be applied in order to convince the population to make the change. On the one hand, consumers would be more prone to change should they not have to bear any upfront costs. Furthermore, on the other hand, if there is a clear plan and date for the phase-out of natural gas, consumers would be confident that they need to stop using natural gas as a heat source. The latter could be combined with fiscal measures such as the aforementioned carbon tax and/or a penalisation or bonification in the property tax.

Furthermore, consumers may also be more willing to change if the company is operated as non-profit or some sort of co-ownership is available. The first option is the option in Denmark by law, and the second possibility could be attractive to the citizens thanks to the long cooperative tradition in the Basque Country.

These measures would need to be accompanied by a massive engagement campaign with the citizens, so they gain knowledge of the advantages of the new heating solution and the necessity of a change.

3. Dublin

The city of Dublin, the Irish capital and largest city in the country, is a coastal city, just as Bilbao, and hosts an urban population of approximately 1.34 million (2016) which, as can be seen in the map presented in Figure 28, predominantly lives in moderately dense settlements quite evenly distributed among the different city districts. Apart from a few 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 340 MWh/ha), according to the Heat Roadmap Europe projections for the data year 2015.

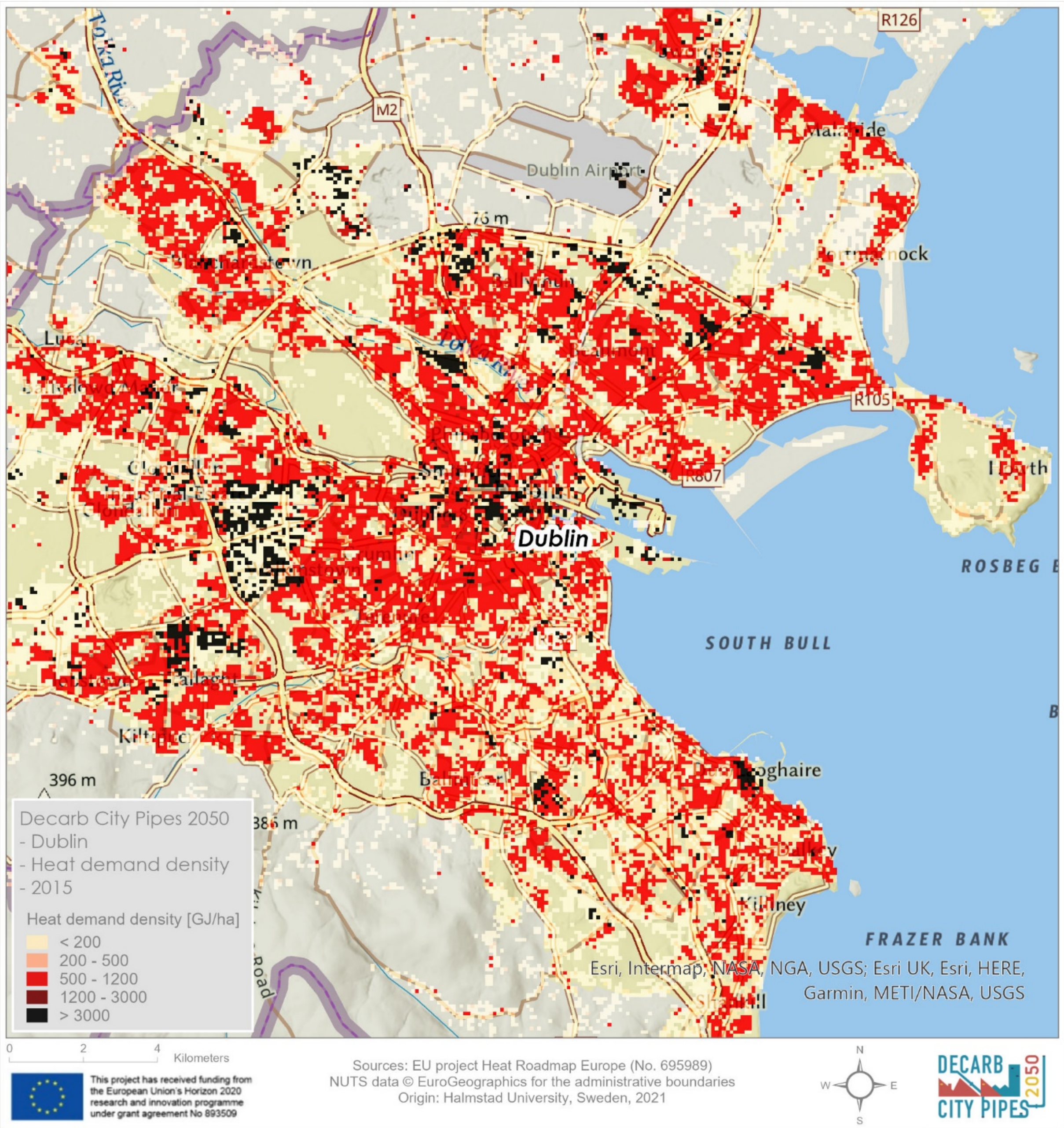

FIGURE 28. MAP OF HEAT DEMAND DENSITY BY HECTARES IN THE CITY OF DUBLIN AND SURROUNDINGS. SOURCES: [9, 27].

The local working group in Dublin is led by Codema, Dublin's energy agency, and gathers city and county local authorities, utilities (electricity, gas, etc.), national level department representatives on environment and climate, as well as several expert organisations and institutions, for example the Geological Survey Ireland (GSI), which investigates deep geothermal assets in the area as a possible base load heat resource for district heating, the Sustainable Energy Authority of Ireland, which is responsible for developing a national heat plan, and representatives from the Citizens through Sustainable Energy Community initiative. The LWG assembles in larger meetings to discuss umbrella topics which require overall consensus and attendance by all stakeholders, as well as in smaller topic-driven group meeting with relevant stakeholders only.

According to the information shared by the LWG within the project so far, key topics discussed have initially addressed main barriers to the development of low-carbon heating and cooling technologies and infrastructures in Dublin, and what realistic alternatives really are at hand to transition from a heavily natural gas and electricity dominated heating and cooling supply based primarily on individual solutions.

The local working group has been asking themselves what is district heating? What do we know about it? What is heat planning and how could the city of Dublin be characterised in terms of future zoning of city districts by suitability to different system solutions? What kind of futureproofing of buildings for connections to district heating should be considered, and, in general, what kind of precarious initiatives in the formulation of building and heat market regulations should not be forgotten already at the outset? What exploitable alternative heat resources are actually available in our city, and, in short, what skills, tools, and knowledge, what policies, what regulatory developments and implementations, what financing, resourcing, and planning, needs to be considered for a transition of this magnitude and consequence?

And these are of course all the right questions to be asked by any local working group in the face of the task to decarbonise a city's heating and cooling supply.

3.1. Heating and cooling outlook 2050: Dublin

Of the six cities in the Decarb City Pipes 2050 project, which are presented in this report, Dublin is in one particular sense very unique. The reason is that, if the cities would have been placed in either of two groups at the start of the project (July 2020), based on whether there is an existing large-scale district heating system in the city or not, Dublin is the only city for which this status has changed in the year that has passed since. This is due to the notification from Codema[24] in the early spring of 2021 that the South Dublin County Council had decided to build the Tallaght District Heating Scheme, the first large-scale district heating system in the whole of Ireland of its kind, which moreover will utilise data centre excess heat as its main heat source.

It is apparent from this fact, and from the successive notification that there apparently is yet another district heating system being constructed in the harbour area, the Dublin Docklands District Heating System[25] (where Codema is likewise partaking), that the city if Dublin is taking the bull by the horns by firm and confident action. And, as briefly mentioned above,

[24] Codema, Tallaght District Heating Scheme: https://www.codema.ie/projects/local-projects/tallaght-district-heating-scheme
[25] Dublin District Heating System: https://www.dublincity.ie/sites/default/files/2021-01/business-model-options-exec-summary-aug-2020.pdf

there is good cause for this given a current situation in which space heating and domestic hot water demands are met by fuel sources that are fossil down to principally the last kilowatt-hour. According to the shared information from the LWG, the current distribution of fuel sources in residential dwellings reads: Gas 74% (assumedly mainly individual), Electric 18% (mainly direct), Oil 7%, and Coal/Biomass 1% (percentages relating to the share of dwellings supplied by each respective fuel source). Add to this the typical dilemma that most of the energy infrastructures to provide these fuel sources, i.e. electricity and natural gas grids, are owned and operated not by local, but by national-level utilities, which means that the local administration has limited influence and access.

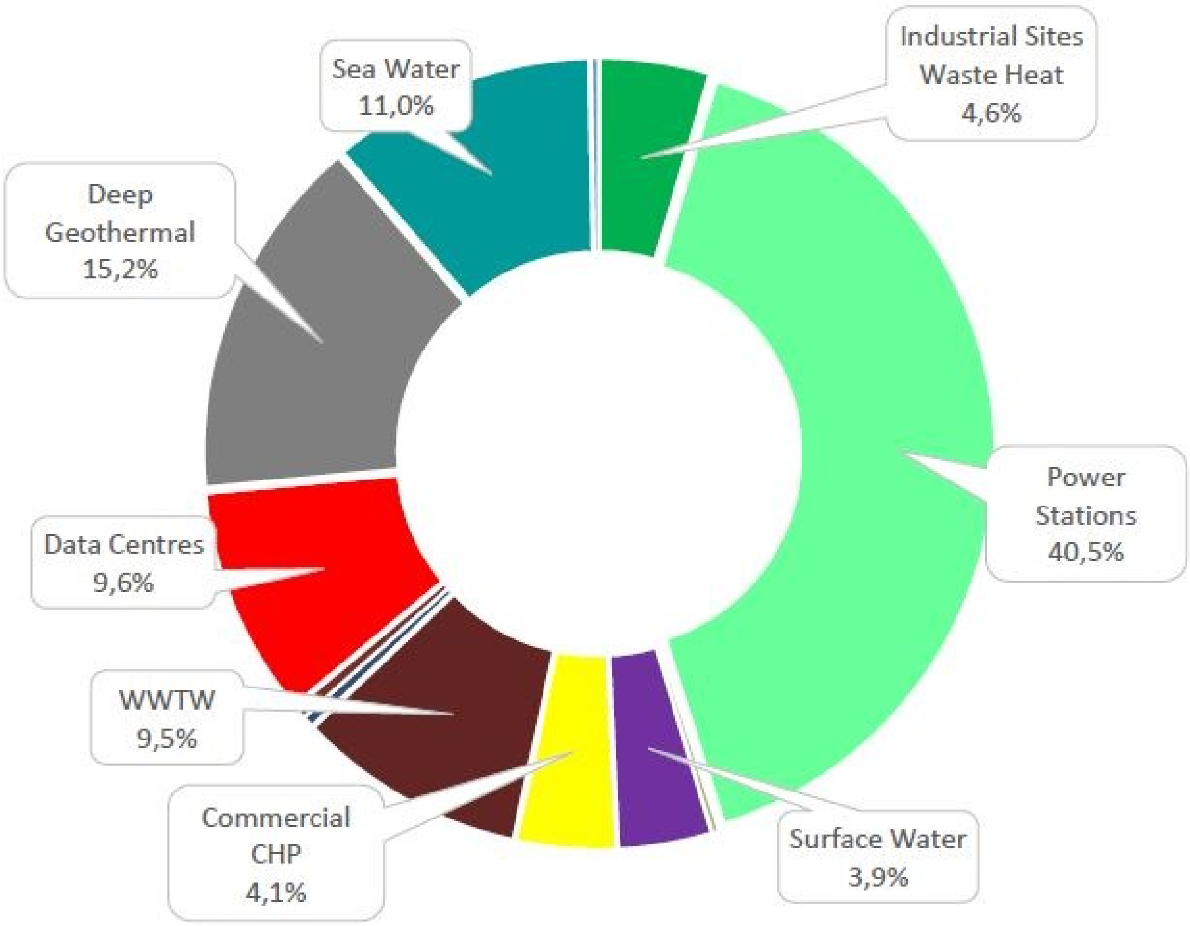

FIGURE 29. HEATING AND COOLING SUPPLY OUTLOOK PRESENTED BY THE LOCAL WORKING GROUP IN DUBLIN.

The local working group in Dublin has made several inquiries into possible alternative heat sources by which to break this fossil dependency and their resulting heating and cooling supply outlook is presented in Figure 29 (this outlook is well in alignment with the examples presented in Figure 31). From this pie chart it is clear that excess heat recovery from power plants and commercial Combined Heat and Power (CHP) units constitute close to half of the anticipates future supply. The actual fuel sources to be used in such installations are not further detailed in the current material. However, the remaining supply will be provided by a diverse palette of various carbon lean sources, such as deep geothermal (~15%), sea water heat pumps (~11%), data centres (~10%), waste water treatment plants (~10%), as well as minor contributions from industrial excess heat (~5%) and surface water heat pumps (~4%).

The local working group in Dublin is also performing investigations directly into the current building stock, especially concerning the impact of retrofitting by developing demand profiles for various building types (by the use of archetypes augmented by real world data on demands and other building properties where available) in search of performance gaps and possible rebound effect. By such activities, the LWG is mapping the current building performance, which is expected to render knowledge about where, in what areas of the city, retrofitting most likely should be most cost optimal and therefore be tackled first.

In addition, investigations are also being performed into other related areas, such as spatio-technical analyses of buildings currently suitable for heat pumps and various modelling of the electricity network in terms of hourly demands and the need for grid reinforcements (and associated costs) as a function of expanded use of compressor heat pumps. Also, the area of so-called “green gas” is examined, by for example spatial modelling of the gas network with coupled assessments of the suitability for blending in hydrogen (at 20% and 100% concentration levels). In relation to the latter, and in recognition of different temperature demands in industrial versus building applications, systemic concerns regarding optimal integration levels of such demands in pursuit of feasible hydrogen facilitation, are also part of these investigations.

Interestingly, the local working group in Dublin has also included non-technological areas of investigation into their analytical portfolio, where, for example, the risk of energy poverty as a function of unemployment has been spatially analysed (as illustrated in the map presented in Figure 30). With an urban population growth expected from 2016 to 2036 at approximately one percent per year (0.9%, according to the shared material), socioeconomics is a factor of increasing importance in the years to come, and certainly, therefore, worth investigation[26].

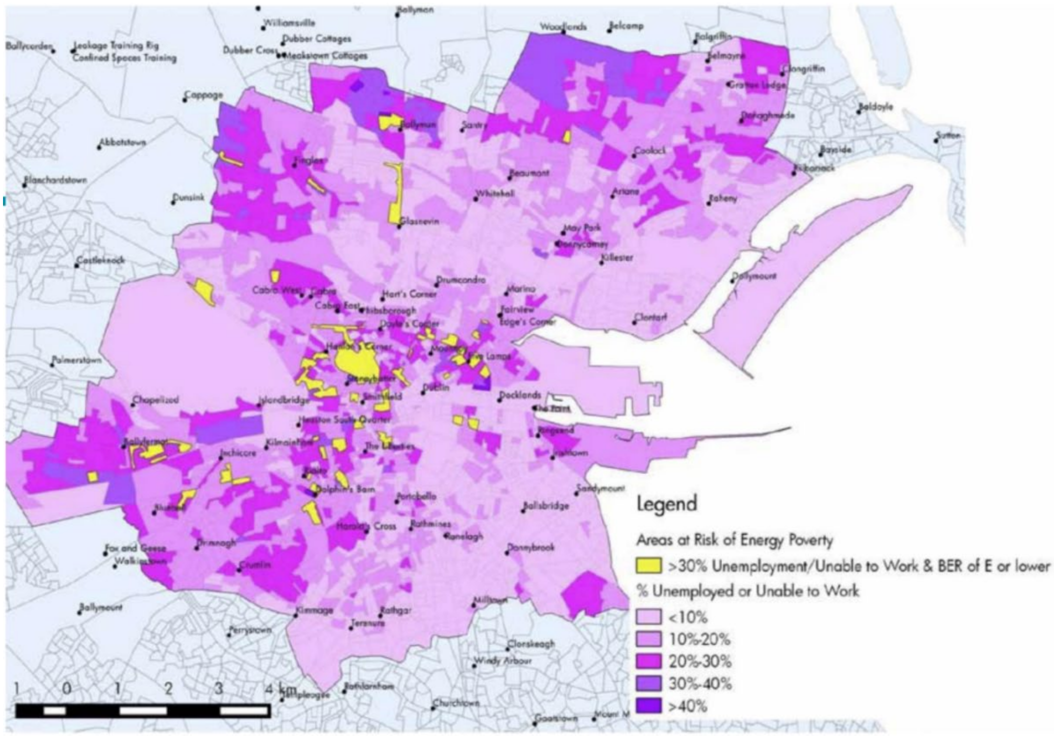

FIGURE 30. MAP OF SOCIAL AND ECONOMIC IMPACTS FROM ENERGY POVERTY AND UNEMPLOYMENT IN DUBLIN.

[26] For further reading on the ongoing work in Dublin, see also the Dublin Energy Webmaps at: https://codema-dev.github.io/dublin-energy-webmaps/

3.2. Draft recommendations: Dublin

The first, and lasting, impression of the local working group in Dublin is that it already has created and generated a solid understanding and comprehension of its local situation. The group appears to be extremely well represented and organised, there seems to be a strong consensus and, in fact, a shared feeling of satisfaction and joy for the achievements already made. The challenge is massive of course, but this shared feeling is evidence of the capacity to appreciate a collective good and might prove vital for the continued progress and success. What then could be said as draft recommendations? Well, what about waste management and the option of Waste-to-Energy incineration (absent in Figure 31)? Waste management is not mentioned in the shared material so far so one wonders what the intention is regarding this option. Is it export of wastes or are you at a point when you are ready to make own use of this societal snag as a domestic resource for heat generation?

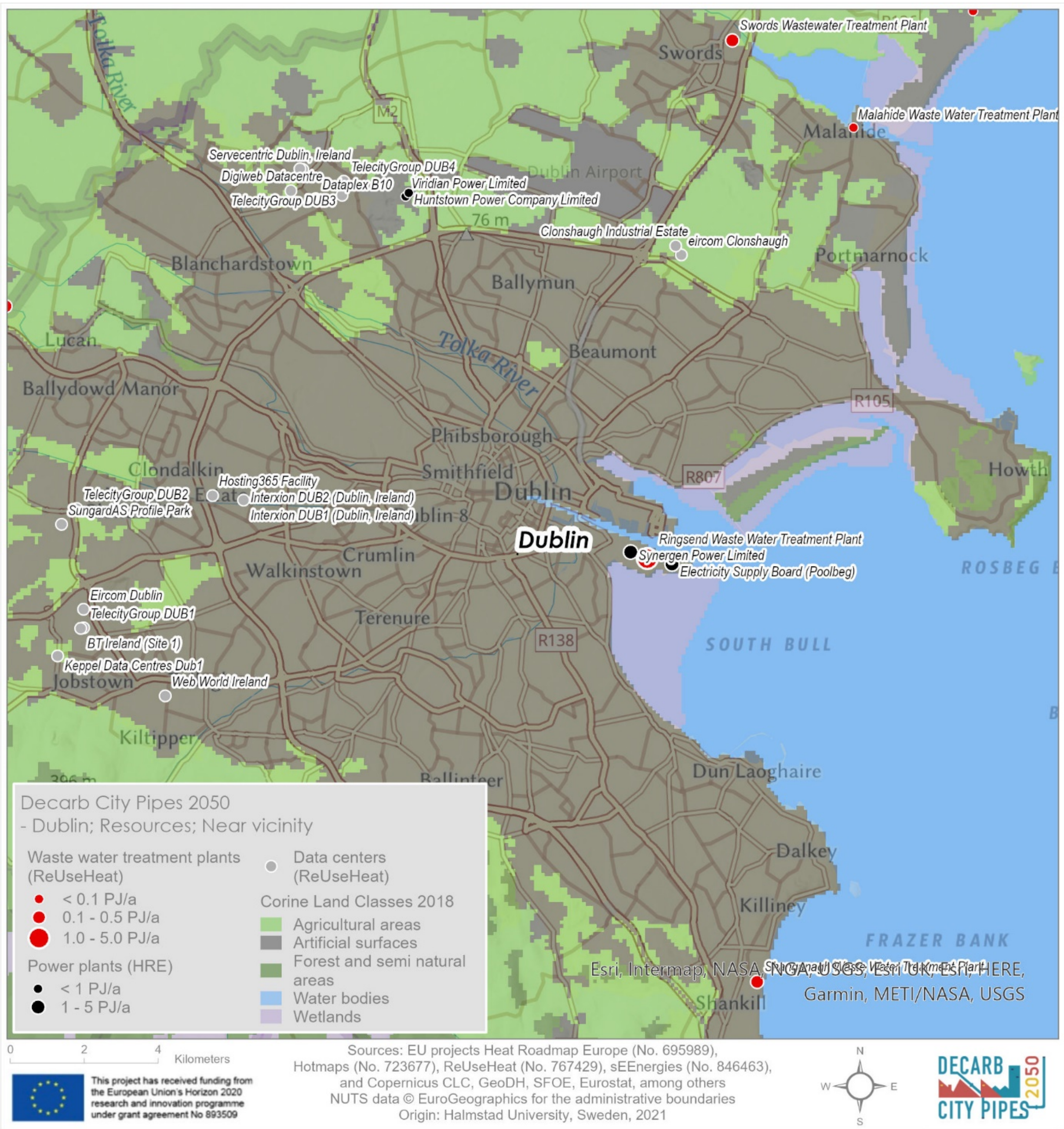

FIGURE 31. EXAMPLES OF HEAT RESOURCES IN DUBLIN AND ITS NEAR VICINITY. SOURCES: [9, 12, 13, 28].

4. Munich

Unlike the cities of Bilbao and Dublin, the remaining four cities to be presented in this report, Munich, Rotterdam, Vienna, and Winterthur, all have existing large-scale district heating systems in operation. In the case of Munich, the district heating system, being one of the largest in Europe with over 800 kilometres of steam and hot water networks (according to Wikipedia[27]), has a long history, several large production units, and supplies close to half of building heat demands in residential and service sectors (own estimation of the average connection rate is in the range of 45% - 50%, based on 2015 data from the HRE project).

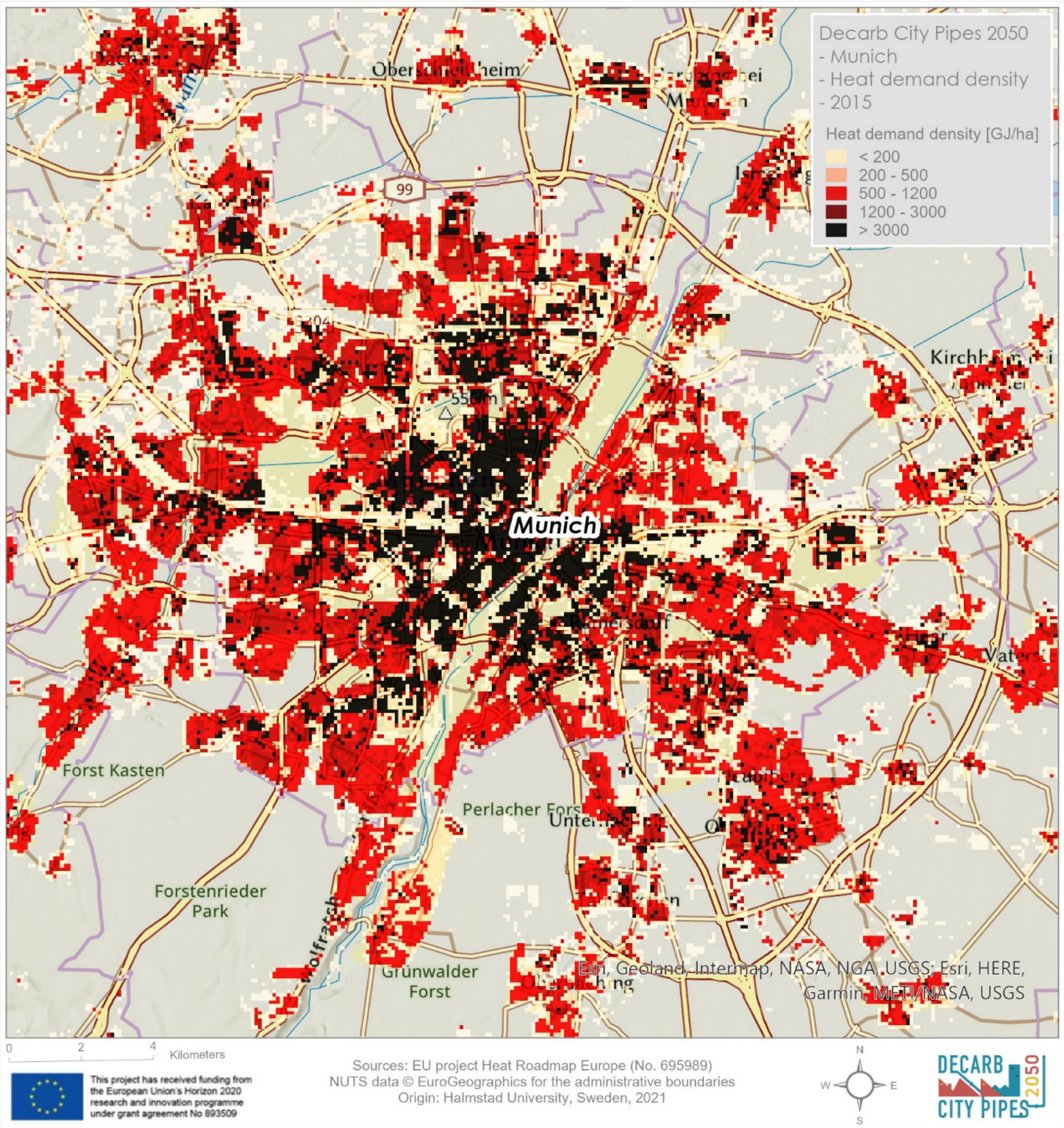

FIGURE 32. MAP OF HEAT DEMAND DENSITY BY HECTARES IN THE CITY OF MUNICH. SOURCES: [9, 27].

[27] Stadtwerke Munich: https://en.wikipedia.org/wiki/Stadtwerke_M%C3%BCnchen#District_heating

As can be seen in map presented in Figure 32, the city of Munich displays the typical characteristic features of very large cities (the city of Munich counts approximately one and half million inhabitants), where the city centre is very dense (heat demand densities at or above 3000 GJ/ha), and where this density successively decreases the farther away from the inner urban areas one gets. Still, most of the core city should be rather suited for feasible district heat distribution due to the strong coherency and compactness of these heat demand densities.

The local working group in Munich is led by the City of Munich and is an assembly with representatives from different departments of the city administration, from Stadtwerke München (SWM), from different utilities, as well as from city-owned housing and refurbishment companies. The group meets quarterly and is organised by means of different sub-groups under a core group, the objective of which being to channel particular topics and projects for special discussion and address in the sub-groups while overall topics, such as citywide strategies for Munich's future energy supply, dedicated energy planning etc., is dealt with within the core group.

In its support, the local working group may also be said to enjoy the benefits of a city administration with a long track record of proactive city planning towards energy efficiency and sustainability. A first so called "Urban Development Plan" was introduced as early as 1963, whereafter several updates have followed in the decades that have passed since. In 2008, the city adopted the first version of an "Integrated Action Programme for Climate Protection in Munich", which have later been followed by a second programme in 2013, and a third in 2015. As far as discernible from a distance, the most recent developments in this respect, refers to the contextual commitment assembled under the new "Energy Use Plan for Munich"[28], which is a database-supported planning instrument made publicly available through an energy portal[29].

From the initial information shared by the local working group, where they have asked themselves what the biggest obstacles to the decarbonization of the heating and cooling supply in Munich are, concerns have been raised regarding jurisdictional circumstances (German Law (e.g. §556c BGB –German Civil Code), the signification of which will have to be returned to in a later version of this report), political will and funding opportunities, as well as more technical concerns such as the cost of district heating for house owners and tenants, and the large number of buildings in the city that needs to be retrofitted in the coming years.

As an output from the interdepartmental work in the city administration, the above mentioned "Integrated Action Programme for Climate Protection in Munich" has resulted in several concrete climate protection programs over the years, with specific targets for greenhouse gas emission reductions and reduced specific heat demands in buildings etc. In the climate protection program for 2010, there is mentioned a carbon dioxide reduction target (set by Munich's City Council) which consisted in a 10% reduction in emissions every five years and a 50% reduction of emissions by 2030 compared to a base year of 1990. It is likely that these targets are now outdated, but the most recent agreements have not been available during the preparation of this report.

[28] https://www.ffegmbh.de/kompetenzen/energiekonzepte/237-energienutzungsplan

[29] Munich energy portal: https://geoportal.muenchen.de/portal/energie/

However, there seems to be ongoing discussions in Munich to the effect that per-capita CO_2-equivalent emissions are to drop to 0.3 tonnes per year by 2035 (which is substantial in comparison to current levels, stated at some 6.5 tonnes per year according to the shared information). For any city, with or without current large-scale district heating systems in operation, this is a challenge that somehow must include a fundamental transition from the dependency of fossil-based fuels and energy sources, to an increased use of renewable and recovered residual sources. And, the city of Munich has a plan, as always, and it may very well prove to be a blueprint solution for many other central European cities to be inspired by in the future.

4.1. Heating and cooling outlook 2050: Munich

The heating and cooling outlook of the local working group in Munich has, in short, two major focus areas, both of which must be considered as spot on. On the one hand, the analysis, understanding, and contextualisation of how to reduce heat demands in the current building stock by way of major refurbishments, and, on the other hand, the investigation, planning, and facilitation of converting the current district heat supply from fossils to renewables (which implicitly includes conversion also from relatively high to lower distribution temperatures).

Regarding the first focus area, the city has already established a very rich foundation, consisting of statistics, data, and various models and map tools, by which to analyse and understand the current building stock. All in all, there are apparently roughly 170,000 heated buildings in the city (once again, according to shared information from the local working group), of which some 40,000, currently with individual heat supplies, and another ~20,000, currently with district heat supply (amounting to a total of some 60,000 buildings, or ~35%), which will need retrofitting before 2030 if to meet emission reduction targets. An age structure analysis reveals that more than half of the buildings were built before 1978, and these building are likely those with the greatest need of refurbishments.

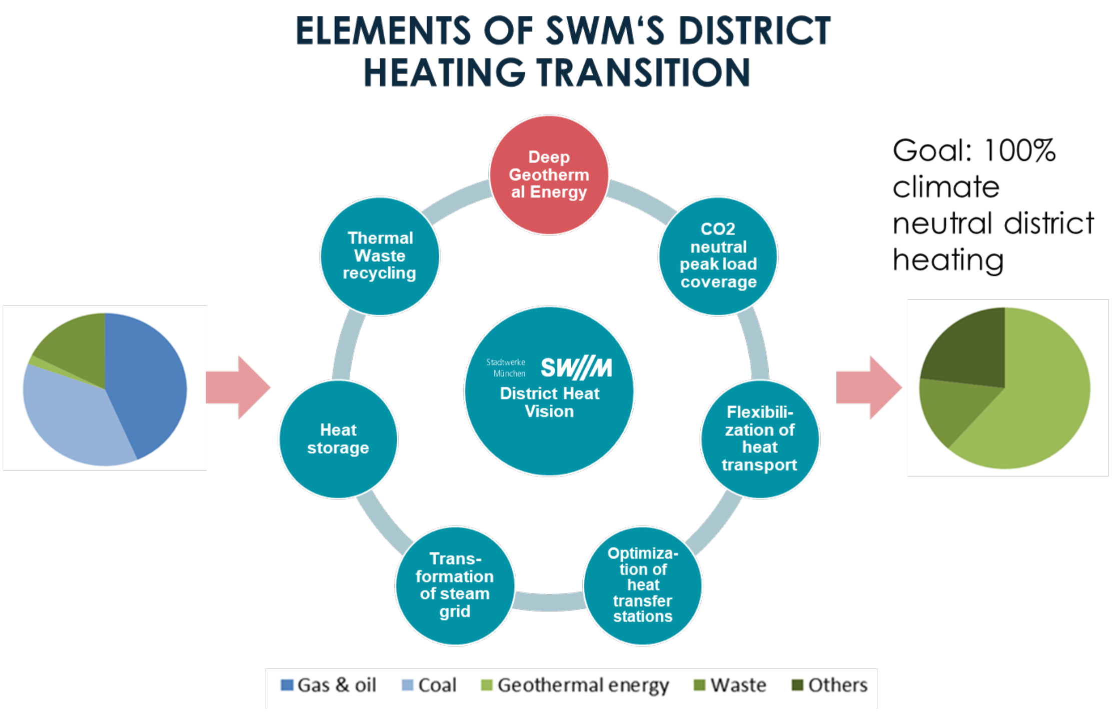

FIGURE 33. ELEMENTS OF SWM'S DISTRICT HEATING TRANSITION.

As for the second focus area, Stadtwerke München, together with the city of Munich, has since several years back recognised deep geothermal heat as the major alternative to explore as a future green baseload supply to its district heating system (see Figure 33), and with good reasons. There have been plenty of news feed articles about this discourse in recent years[30], and the most recurring arguments in favour of deep geothermal are that:

- Deep geothermal energy has the potential to provide renewable heat to entire cities.
- Is an important factor for security of supply thanks to its baseload capacity.
- It can be the heat source with the lowest production costs if heat grids already exist.

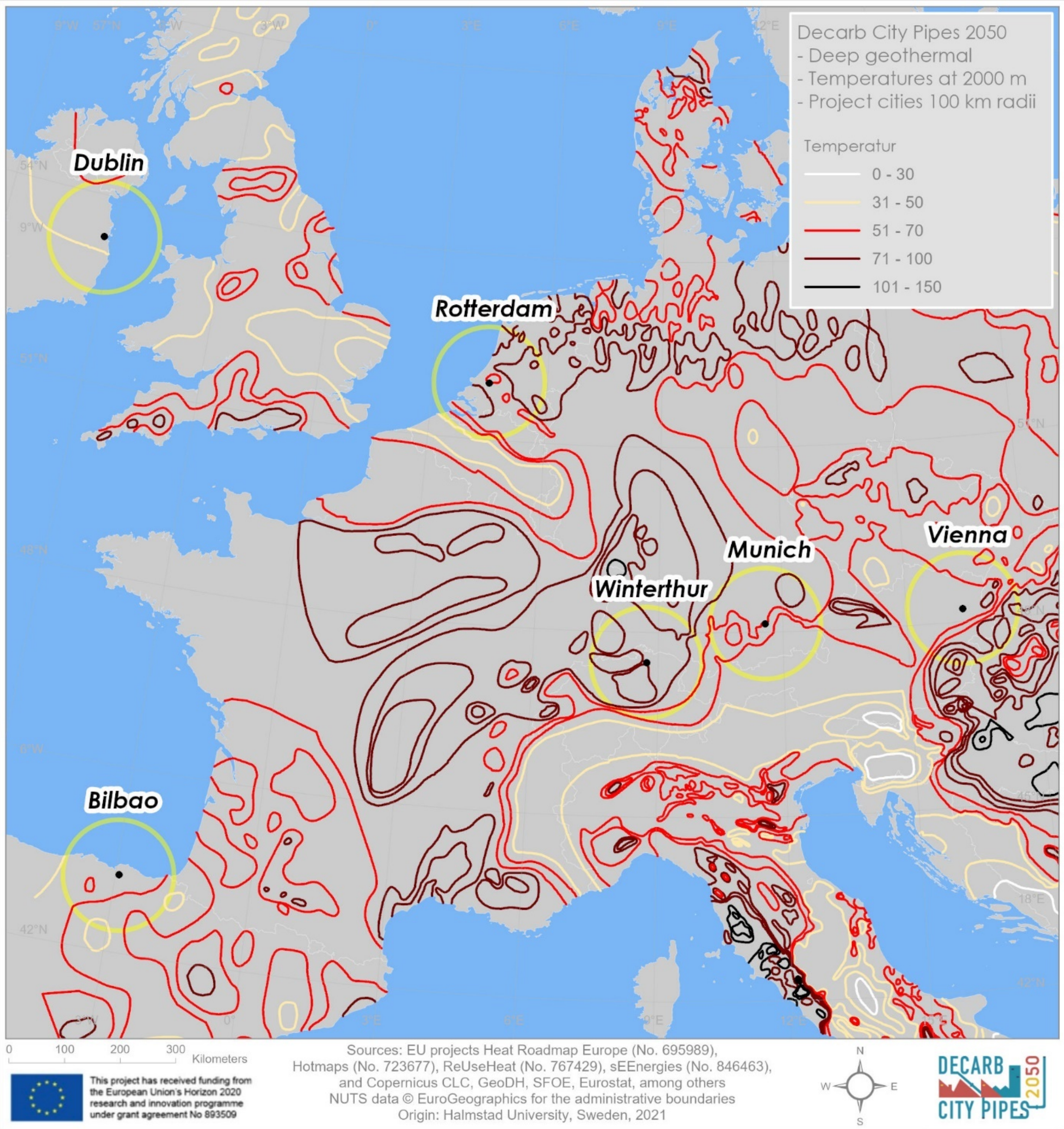

FIGURE 34. DEEP GEOTHERMAL TEMPERATURE DISTRIBUTION AT 2000 METER S DEPTH (˚C) WITH THE SIX PROJECT CITIES OUTLINED BY 100 KM RADII CIRCLES. SOURCE: OWN ELABORATION OF PLATE 3 MAP IN [64].

[30] See for example (2021-06-27): https://www.thinkgeoenergy.com/heating-with-geothermal-the-ambitious-plans-of-munich-germany/

This second focus area elaborated in the city of Munich is, as indicated above, likely a consideration that many other cities in Europe would find interesting and relevant once the process of strategic heat planning and decarbonisation of heating and cooling supply structures have been integrated into the city management, and indeed so also for several of the other project cities. For this reason, and to provide further guidance to the participating cities, the authors have prepared the map presented in Figure 34. This is a map of the temperature distribution at 2000 meters depth, originally published as Plate 3 in the 2002 Atlas of Geothermal Resources in Europe from the European Commission [64], which was scanned and further elaborated into the contour lines visible in the map.

The final energy demand of all heated buildings in Munich amounts according to the shared information to 12.2 TWh per year, a total annual volume which consists of 7.0 TWh per year of natural gas (57 %), of 4.2 TWh per year district heat (34%), of 1.0 TWh per year oil (9%), and some minor additional contributions from direct electric heating and biomass. As part of their work, the city has mapped the spatial distribution of this current heat supply across the city, as presented in the map in Figure 35[31]. The pattern is quite clear: district heating has mainly been developed and used in the densest, and therefore most economically feasible, city districts, whereas individual boilers, in this case mainly using natural gas, is the standard solution in most districts with lesser levels of heat demand density. In fact, a comparative study of the heat demand density map in Figure 32 and the map of the current heat supply in Figure 35, confirms the general rational for using heat demand density as a proxy for the DH feasibility, while also providing a first order indication of new DH areas to explore.

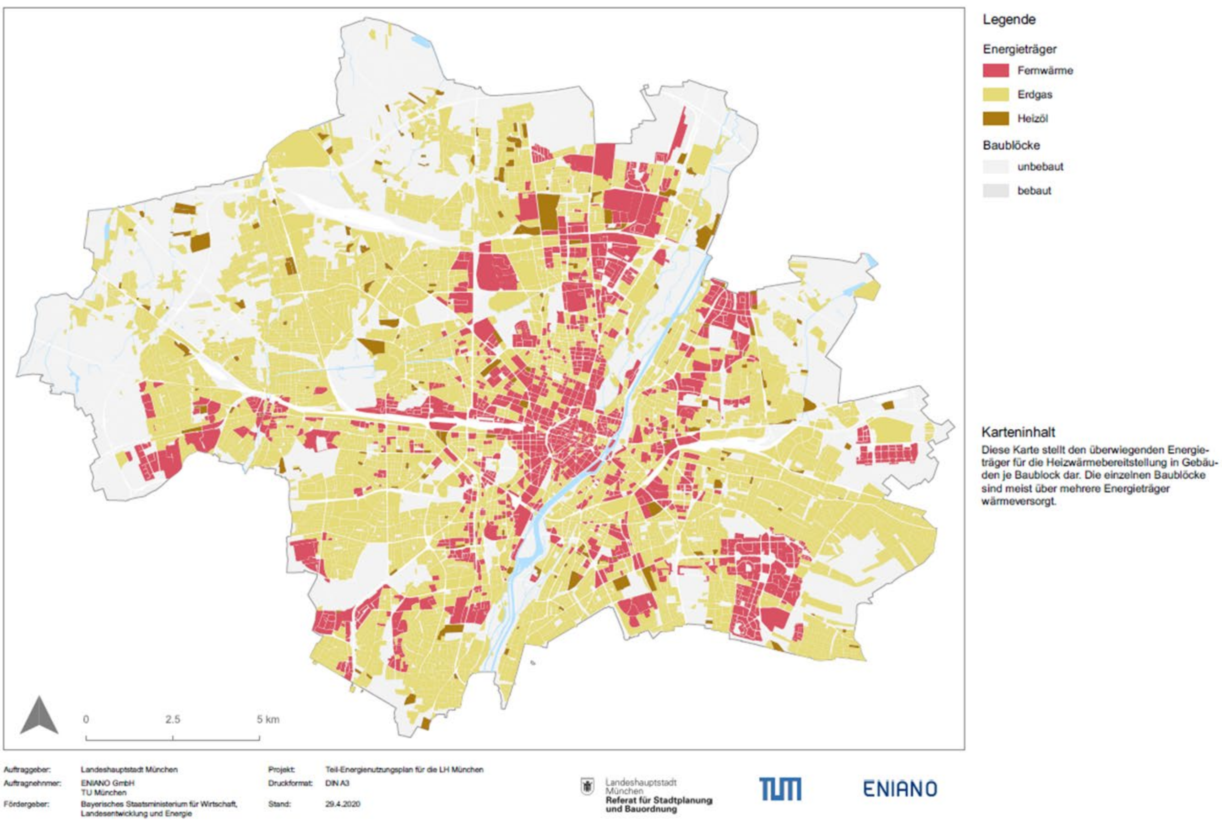

FIGURE 35. MAP OF THE CURRENT HEAT SUPPLY IN MUNICH BY TYPE OF FUEL AND ENERGY CARRIER.

[31] Partial energy utilisation plan for the heating and cooling sector of the city of Munich: https://www.ar.tum.de/en/klima/research/completed-research-projects/energy-use-plan-munich/

And again, as always, this is exactly what the local working group in Munich, together with the Stadtwerke Münich, is doing as elements in their vision to transition the district heating system of Munich (as principally outlined in the flow chart in Figure 33 above and as spatially anticipated in the map of their future heat supply scenario, presented in Figure 36).

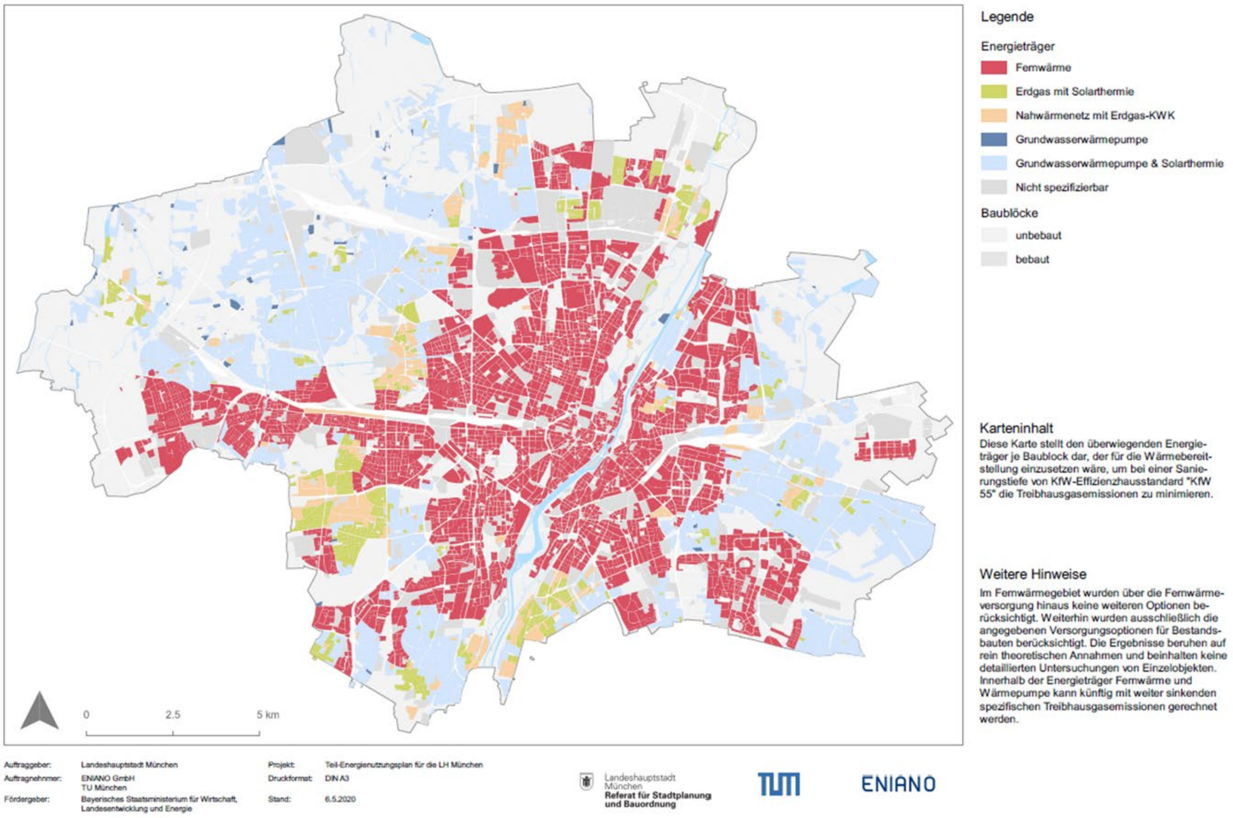

FIGURE 36. MAP OF THE HEAT SUPPLY SCENARIO IN MUNICH BY TYPE OF FUEL AND ENERGY CARRIER.

From the map in Figure 36, it is clear that Munich aims at expanding district heating across the complete inner city area, which indeed should be realistic even when considering building retrofits (with reduced specific heat demand as a consequence) since the future system is planned to operate at lower distribution temperatures. Assumedly, deep geothermal will constitute the baseload backbone in this system, where additional supplies could be those possible from industrial excess heat and other low-temperature excess heat resources, such as wastewater treatment plants, data centres, and metro stations, which all are represented heat resources in the Munich map presented in Figure 37.

Noteworthy, the city also widens the scope in the Figure 36 map, and suggests low-carbon alternatives also for the outer city areas, where the use of natural gas in combination with solar thermal applications is one example, and ground water individual heat pumps are conceived as another. In addition, islands of district heating (“nahwärmenetz”), with energy efficient cogeneration of electricity and heat, is also part of the proposed solution.

4.2. Draft recommendations: Munich

To a city with such impressive tradition and structure when it comes to strategic planning, with such a high level of comprehension and experience, and with such eager ambition and strive to accomplish a better heat and cooling supply system for the day after tomorrow, what can be said that isn´t already understood and clear long ago?

Well, for the time being, just a few words on the transition to lower distribution temperatures in the district heating system, which in itself is a real challenge. Are you going to replace the current pipe network or use the same pipes but at lower temperatures? Or, are you planning to obtain overall lower system temperatures by expanding the current system with dedicated low-temperature branches? How will you manage the consequences of reduced specific building heat demands due to retrofits while at the same time reducing the system temperatures? In relation to this, what is your strategy to maintain and improve the competitiveness of heat distribution? Densification of whole city districts? Requirements for obligatory network connection if located in certain city districts to obtain higher connection rates? Some final rhetorical questions to indicate possible other grey areas may be that of, as for Dublin, what about waste management and in particular Waste-to-Energy incineration? Is this not part of the plan? And, what about peak load supplies?

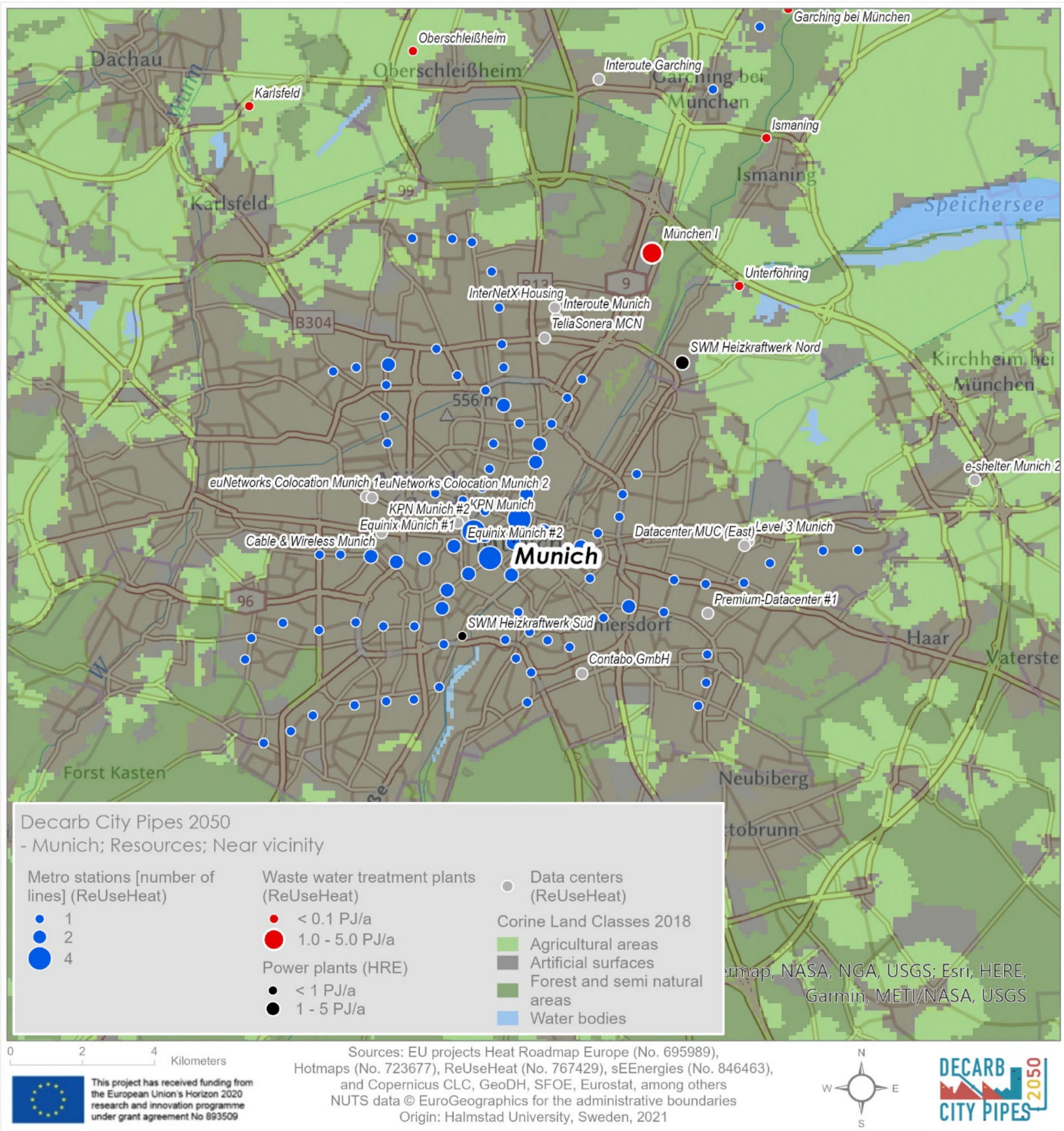

FIGURE 37. EXAMPLES OF HEAT RESOURCES IN MUNICH AND ITS NEAR VICINITY. SOURCES: [9, 12, 13, 28].

5. Rotterdam

As has been the case for all the other cities in the project, the local working group of Rotterdam reported in due time (end of May 2021) that the city had reached agreement on a heating and cooling supply outlook 2050 in accordance with milestone 2 (MS2)[32]. However, unlike all the other project cities, the local working group of Rotterdam has not yet made available to the authors a draft outlook of this H/C supply 2050 broken down to energy carriers so that its contents and meaning may be clearly comprehended.

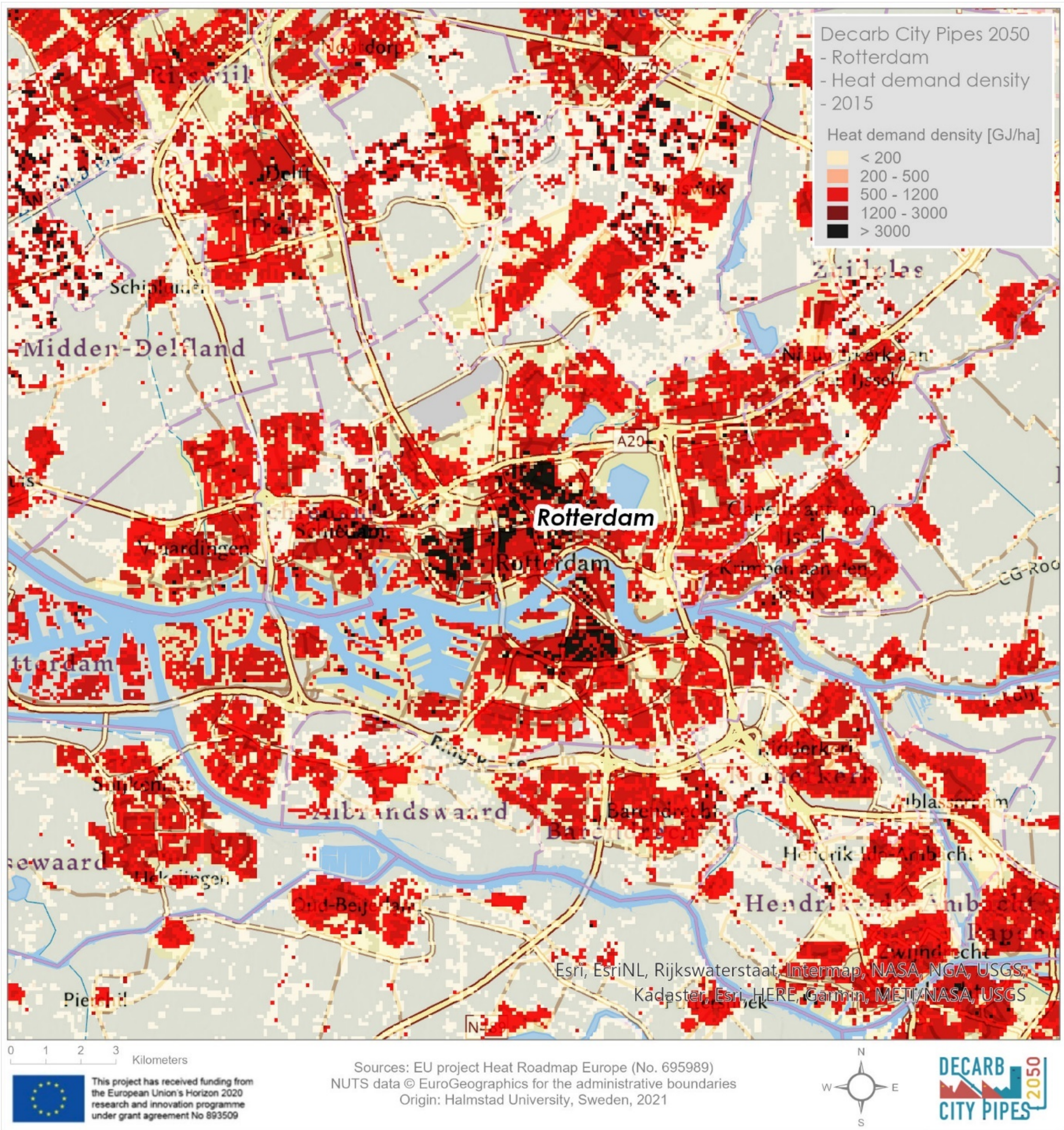

FIGURE 38. MAP OF HEAT DEMAND DENSITY BY HECTARES IN THE CITY OF ROTTERDAM. SOURCES: [9, 27].

[32] As also stated in footnote 1 above, milestone 2 is defined as a "common understanding among LWG with working hypothesis on how to reach carbon-free H/C energy balance". Means of verification: A draft outlook of H/C supply 2050 broken down to energy carriers is available for all cities (except BRA).

For this reason, this section will, for the time being, consist only of some preliminary reflections and comments based upon various generic presentations held by LWG representatives during the course of the project's progression during the past year. By these generic presentations, it is however quite clear that there indeed is a lot of activity and work on heat planning going on the city of Rotterdam[33], which is reassuring. Still, unfortunately, we will all have to wait a bit longer until we can get the opportunity to learn more about the cohesiveness of these activities, and in particular on whatever heating and cooling supply outlook 2050 that the local working group apparently have reached agreement upon.

As observable in the map in Figure 38, the city of Rotterdam occupies both banks of the Nieuwe Maas channel (a part of the Rhine–Meuse–Scheldt delta which leads out to the North Sea), and is neighboured and nested with several other cities in the notoriously dense south-western part of the Netherlands. 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, in the United Kingdom). These characteristics, that is, a bias of moderate 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 (in the average range between 500 GJ/ha to 1500 GJ/ha, as a hands-on assessment based on the map).

The local working group in Rotterdam is led by the Sustainability Department at the city administration (the municipality) of Rotterdam, and consists of an inner circle (the municipality staff) and an outer circle with representatives from DH companies, grid owners (public and private), housing cooperation's, and other likely stakeholders in the region not further specified at this moment. The work among these collaborators have been divided into three levels: Strategic, Tactical, and Operational. Notably, under the first (Strategic), a special group, the "Regional Energy Strategy Group", has been formed to capture the regional perspective (the group apparently assembles 23 cities and grid owners, according to initial information shared on the organisation of the LWG)[34]. It appears further that the inner circle, that is the municipality staff, are highly dependent on various inputs from the "outer circle" parties, with which they state to have regular contacts. Eventually, also politicians are expected to become involved at a later stage.

The work on three different levels may prove very appropriate, where on the strategic level the LWG has conceived of an "Energy System Vision", on the tactical level a "City Transition Vison Heat", and where it, on the operational level, foresees work with several different district-oriented projects. However, it remains to be seen. There is also an apparent risk of confusion due to over-elaboration, if the structure and the actors involved in the strategic heat planning initiative becomes too complicated and too alienated, respectively. The key operational functionality of the local working group should be its mandate and capacity to steer the whole process towards the agreed strategic objectives, and, for natural reasons, this mandate and capacity may very well be lost if the multitude of different perspectives, activities, and parties involved, becomes overwhelming and unmanageable.

[33] See for example the Energy Strategy Rotterdam Region -The Hague: https://www.resrotterdamdenhaag.nl/

[34] See V. Forstinger, J. Neyer (2021). Report on the setting-up of the Local Working Groups, Deliverable 2.1. Decarb City Pipes 2050 – Transition roadmaps to energy efficient, zero-carbon urban heating and cooling.

5.1. Heating and cooling outlook 2050: Rotterdam

Next to Utrecht, which is recorded for having put into operation the first Dutch district heating system in 1927, Rotterdam became the second city in the Netherlands to develop a large-scale system, when, in 1947 (after the second world war), a system was built as part of the restoration of a severely damaged city district. Despite this, Rotterdam has, as most other cities in the region, developed a deep dependency on natural gas as the main energy source both for power and heat generation, both in individual as well as in central applications.

According to personal notes taken during project meetings (spring 2021), where representatives from the local working group in Rotterdam has commented upon the current situation in the city, district heating and electricity seem to be appreciated as the two main alternatives to reduce the natural gas dependency, in particular for building heat demands in the residential and service sector. Production, and use, of (green) hydrogen is also recognised as an alternative, but anticipated to be more appropriately used in industry, hence, not for buildings.

Discussions on design and arrangement of distribution temperatures of the current district heating systems are apparently also ongoing, where the most recent design developments can be seen in Figure 39. New transmission capacity is being installed by which to exploit excess heat from a more remotely located waste incinerator (the AVR NV (Rijnmond) facility, also visible in the Rotterdam resource map in Figure 40), and, in this way, to substitute older natural gas-based cogeneration capacity which likely will be depreciated.

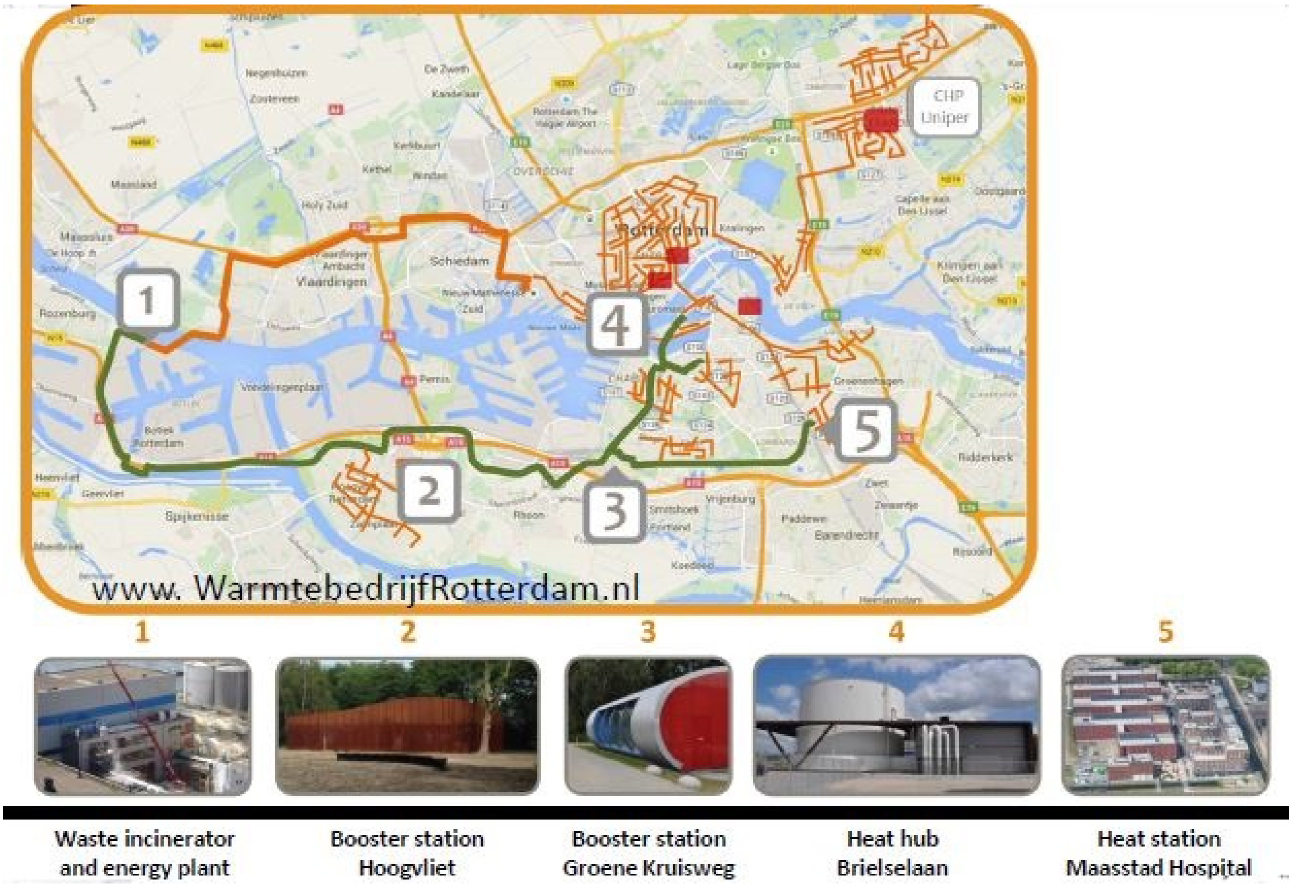

FIGURE 39. COPY OF SLIDE FROM GENERIC PRESENTATION OF "HEAT VISION CITY OF ROTTERDAM" (BY A. MADSEN) WITH OUTLINE OF RECENT DEVELOPMENTS IN THE ROTTERDAM DISTRICT HEATING SYSTEM.

By the same personal notes, it further emerges that, in Rotterdam, it is not the lack of activity, but rather the abundance of it, that appears as potentially problematic. There seems to be just no end to the talking, the discussing, the meeting, the modelling, the mapping, the studying, the analysing, the suggesting, the supposing, the presenting… and so on.

5.2. Draft recommendations: Rotterdam

Based on the above, a perhaps provocative, but in fact positively meant, first draft recommendation is to reflect upon the coordination of the work. In a cultural context which, at least from a distance, seems to cherish so highly the liberty of reflection and speech, on a matter such as this, where it is the communal best that is in focus, it might be relevant to examine executional principles of collective solutions as a balancing complement to eternal discussions of never-ending alternatives in never-ceasing flows of creative ideas.

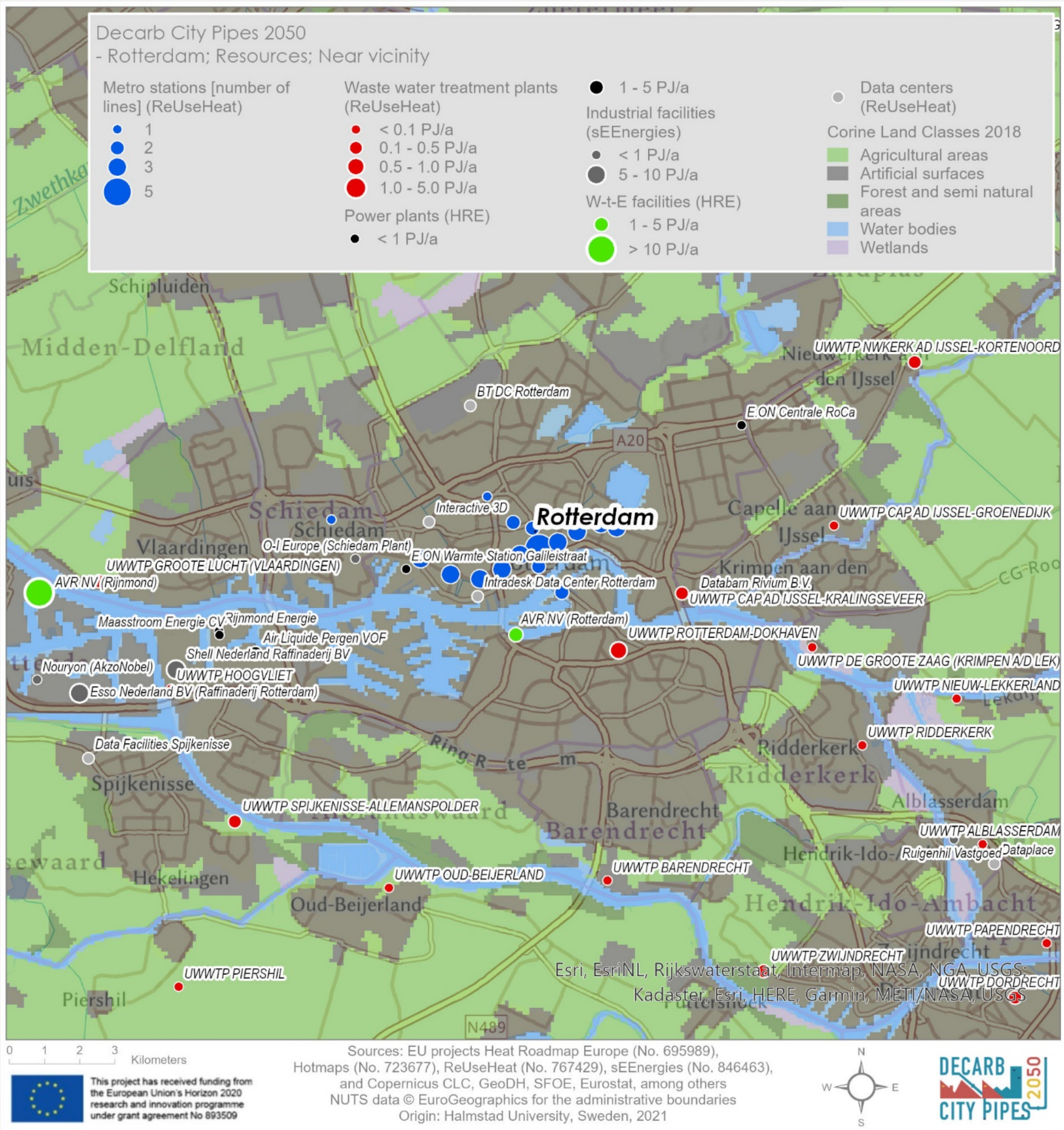

FIGURE 40. EXAMPLES OF HEAT RESOURCES IN ROTTERDAM AND ITS NEAR VICINITY. SOURCES: [9, 12, 13, 28].

With this said, it is very likely that, by the same creativeness and freedom of spirit, the city of Rotterdam will derive solutions and approaches that will shine like beacons of hope for many other cities in Europe and around the world in the years to come. Especially cities with rich industrial and commercial activities going on within, or next to, their city walls – just like Rotterdam. Already at the zoomed-in resolution that was chosen for the resource map in Figure 40, this ampleness is visible, consisting of power plants, waste incinerators, large-scale industries, waste water treatments plants, data centres, and metro stations, just to mention the most palpable. But the resolution could easily have been decreased, whereby a zoomed-out view would have revealed the real magnitude of these opportunities for the whole region as one. In this sense, the initiative to compare “island” and “togetherness” solutions to highlight the regional synergies available, as presented at one of the above-mentioned spring meetings, is recommendable since it ought to be by a regional overview energy system perspective that Rotterdam eventually will pinpoint the final objectives of its strategic heat plan.

Being perhaps the most prominent “excess heat” city among the six project cities, although deep geothermal assets may be available to some degree also here (as observable in Figure 34 above), Rotterdam is likely the city whose local working group will be faced most intensively with the specific challenges associated with excess heat recoveries. Among many, some of these challenges relate to ownership models, contractual arrangements, and principles by which to allocate synergy benefits among multiple stakeholders, which has been discussed by the authors and others in [20, 65, 66]. In extension to this type of practical challenges may be added also those of *Best Available Organisation* (BAO), that is, a principal type of challenges which, again, leads towards the more fundamental issue (briefly touched upon in the introduction section) on how to best arrange future heat and cold supply infrastructures based on mutual benefit and effort.

6. Vienna

Vienna! The Austrian capital, the largest city in the country (as well as in this project) with approximately two and a half million inhabitants in the larger metropolitan area, a world-heritage city like few others, a standing monument over human ability in the fine arts, in literature and music, in architecture and built environment, in culture and science, should require not so much further general introduction in this context. From the heat demand density map of Vienna and its larger metropolitan area, as shown in Figure 41, 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.

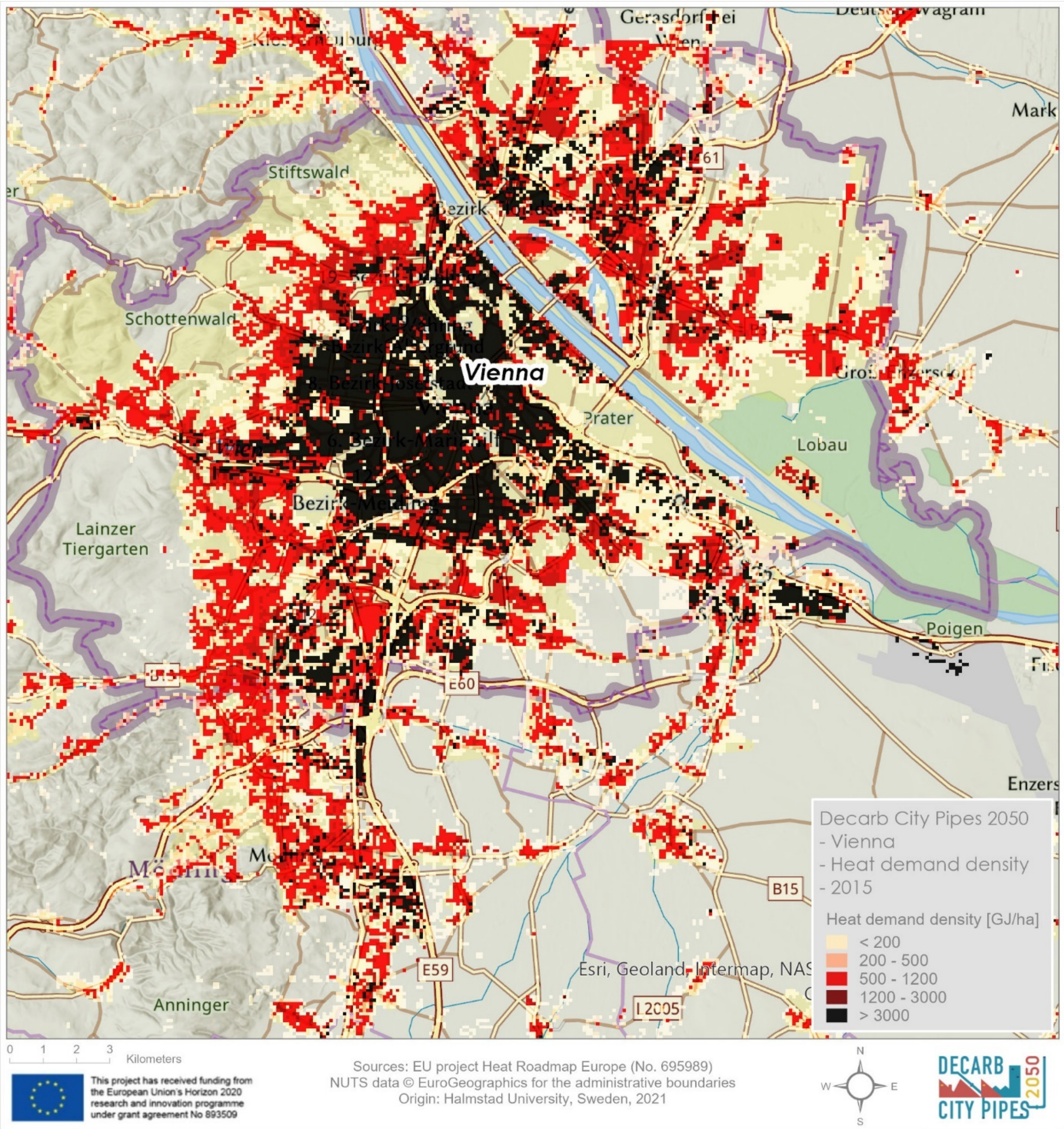

FIGURE 41. MAP OF HEAT DEMAND DENSITY BY HECTARES IN THE CITY OF VIENNA WITH SURROUNDINGS. SOURCES: [9, 27].

The local working group in Vienna is chaired and led by the Planning Department at the City of Vienna, and operates under an institutional design consisting of a steering group (a group with previous experiences from work with for example energy concepts in relation to development of new urban areas) and three subgroups. The first of the three subgroups focusses on the strategic objectives for the future (the city's vision for heating and cooling supply and demand in 2040/2050), the second on spatial energy planning with explicit focus on energy supply options for new buildings and urban development areas, while the third subgroup deals with issues related to spatial requirements of energy infrastructures in general. The tempo for the steering group has initially been set to two to four meeting per year, while the subgroups convene ad hoc and meet more regularly.

In addition to its apt internal organisation, as outlined above, the local working group of Vienna assembles a wide range of external partners and institutions that are involved and contributes to the process. Among these may be mentioned the distribution system operators (DSO's), the city utilities, and other city administration functions, such as city councillor officers as well as municipal departments (e.g. energy department, urban development etc.).The LWG also includes representatives from the building and housing sector and it further invites other experts depending on topic and demand.

The main challenges that Vienna are facing in terms of a decarbonisation of its current heating and cooling supply have been among the first and most urgent topics discussed in the local working group. If put very short, one of these challenges only requires three tiny letters, namely: GAS, and how in the world to get rid of it, but there is more to the picture than just a deep dependency on natural gas and other fossil fuels for power and heat generation (which we also recognise from principally all the other project cities).

As for Munich, once more, also the lowering of building heat demands, that is retrofitting and refurbishments by which to obtain heat savings in the current building stock, represents a challenging area. To this may be added the rate of building demolitions due to age and the rate and mode by which these are replaced by new housing. Should Vienna decide to further develop zoning as a concrete measure by which to control the type of heating and cooling provisions that the city citizens exploit? Or, should the random use of ground (shallow) individual heat pumps be accepted without further ado, under the illusory pretention that free market forces will "decide" what is best?

A third challenging area is that of the current district heating system, which in the case of Vienna is quite unique in the sense of having been constructed with large secondary systems (not building-wise, but neighbourhood-wise), as far as the authors have understood the situation. The current large-scale district heating system is definitely a great asset for the city, but how will it manage to reduce its distribution temperatures and how may larger shares of the total city heat demand be supplied by this central supply rather than by individual solutions? Not to mention, the decarbonisation of its heat generation capacity.

In view of these challenges, the local working group has asked itself the question: "Where do we want to be in thirty years?", which indeed is the proper way to start any strategic heat planning initiative. From here, the group now works to find answers and solutions to meet these challenges, for example, by identifying possible energy supply solutions to break the fossil dependency, by understanding the spatial requirements of current and new energy infrastructures, and by, put short, arduously making their way through Phase 1 of the three-phase framework for strategic heat planning as outlined in Table 1 above.

6.1. Heating and cooling outlook 2050: Vienna

For the first version of its heating and cooling outlook 2050, the local working group in Vienna has used the Smart City Wien Framework Strategy[35] as their main source of reference. According to the strategy, through information shared by the local working group, natural gas constitutes close to half of the total final energy consumption for heating and cooling purposes at current (2016), as illustrated in the graph presented in Figure 42. District heating (Fernwärme), assumedly fired to the most part by natural gas as well, accounts for most of the remaining part with lesser contributions from electricity, oil, and renewables.

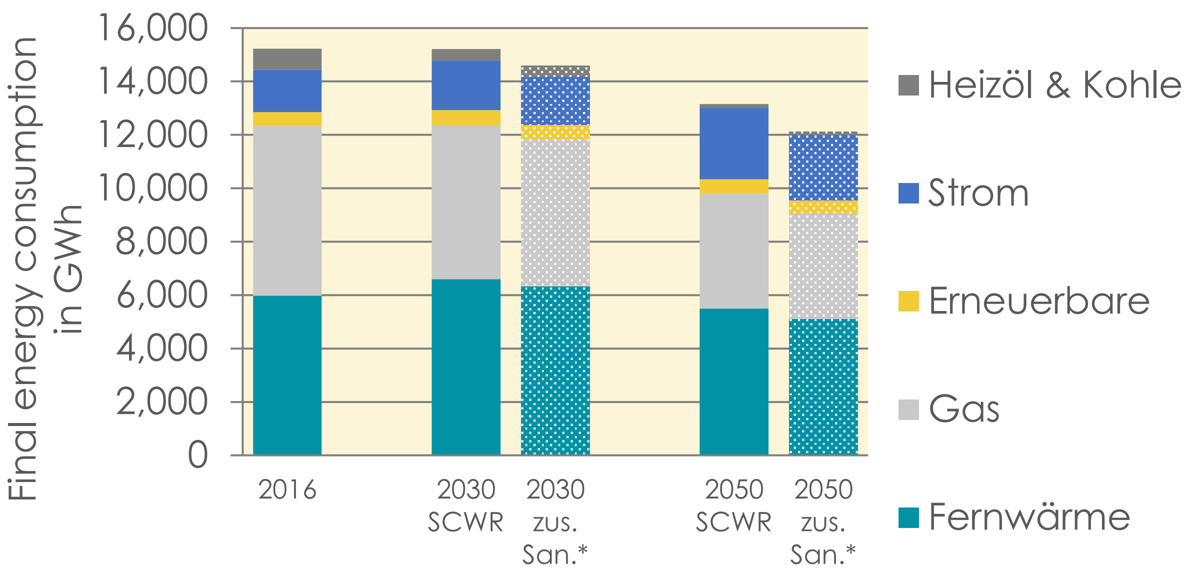

FIGURE 42. CURRENT YEAR (2016) FINAL ENERGY CONSUMPTION FOR HEATING AND COOLING PURPOSES IN VIENNA, AND PROJECTIONS FOR 2030 AND 2050 ACCORDING TO THE SMART CITY WIEN FRAMEWORK STRATEGY (SCWR). *INDICATES ASSUMED RENOVATION RATES 2016-2030/2030-2050: 1,5%/2,0% P.A.

As can be seen in Figure 42, the framework strategy projects reductions in the total final consumption (approximately minus one percentage per-capita and year), reductions which may need to be further enhanced by progressively increased building renovation rates. However, for complete decarbonisation, the LWG recognises that yet additional measures, such as the expansion of the current district heating grid and the further integration of renewables, is going to be needed. The reduction of energy demand in buildings is conceived as requiring the refurbishment of ten thousand to twenty-five thousand flats per year towards 2030 (the city apparently consists of 920,000 flats in total), and thereafter to maintain a steady pace at some 30,000 residential units annually.

The consumption of natural gas is stated as being used primarily for central power and heat generation (approximately two thirds) but to a substantial extent also for individual space heating and hot water preparation purposes (roughly one third). Some natural gas is also used for process heat purposes (~10%). A natural initial reaction and interest has therefore been to investigate into what proportions renewable gasses (biomethane and green hydrogen for example) could possibly be derived and used in the future energy system of Vienna? If feasible, a simple fuel shift from a fossil-based to a renewable-based gaseous energy carrier would mean that the current gas grid could be continuously used without any

[35] The Smart City Wien Framework Strategy: Framework Strategy - Smart City Wien :

major changes being required. Such a prospect would in turn also make unnecessary the otherwise unavoidable conversion of heating system in about 450,000 flats currently supplied by fossil energy carriers. For obvious reasons, a fuel-shift solution of this kind would save the city of Vienna both time and money, but it is questionable whether it in fact ever was realistic.

The fuel-shift logic seems however to have had quite some influence in the formulation of targets for future energy supplies, as expressed in the 2019 Smart City Wien Framework Strategy, which suggested the following key assumptions for the decarbonisation of Vienna's heating and cooling supply (and as outlined also in Figure 43):

- The production of renewables in the city doubles until 2030
- The share of renewable energy sources in final demand reaches 70 % in 2050
- Net-imported electricity assumed to be renewable from 2030
- Gas for cogeneration (CHP) assumed renewable in 2050

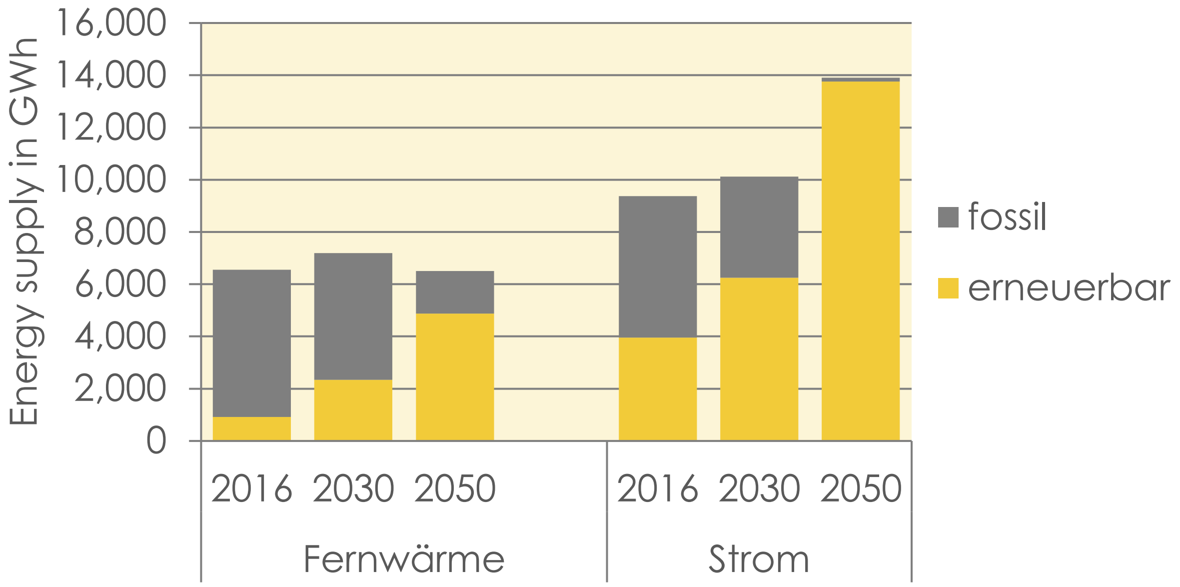

FIGURE 43. CURRENT YEAR (2016) ENERGY SUPPLY FOR HEATING AND COOLING PURPOSES IN VIENNA BY FUEL TYPE FOSSILS AND RENEWABLES, WITH PROJECTIONS FOR 2030 AND 2050 ACCORDING TO THE SMART CITY WIEN FRAMEWORK STRATEGY (SCWR).

During the first half of the first project year (autumn of 2020), the above outlined targets and strategies (that is those originating in the Smart City Wien Framework Strategy) were those presented and conceived by the local working group in Vienna. However, during the second half of the first year of the project's progression (spring of 2021), there was a change of strategy reported by the LWG. It is not known by the authors whether this change was caused by an internal shift of focus within the local work group itself or whether this change was due to external causes. But there is reference to a "new climate and energy target for Vienna" in the shared information from the LWG during the spring of 2021, together with a mentioning of a "new program" and a "new government" although if remains unclear for a bystander whether this refers to a new municipal, city, or national government.

Under any circumstance, from this point and onwards, the local working group of Vienna has been referring to new and more ambitious targets for the city, where, for example, the city is to become climate neutral by 2040 (by the incorporation of concepts such as climate budgeting and climate check for measures and projects). For heating and cooling especially, these new targets imply a complete phase-out of coal, oil, and gas until 2040, by conceptual approaches to be developed until 2022, the expansion of domestic energy generation from renewable sources, and renewable gasses to be used for cogeneration or other high-energy uses only, hence not for low-temperature demands such as space heating and domestic hot water preparation. By such targets, it is clear that a complete revision of previous objectives and measures for the heating and cooling provision in the city is currently taking place.

In response to these developments, the local working group in Vienna has suggested principles and priorities for the phase-out of natural gas which recognises several key elements in strategic heat planning, for example heat demand density, temperature levels, and spatial analysis. These suggestions differentiate current natural gas consumers by the characteristic temperature levels of their demand, where one is gas consumers with a demand for low-temperature heat (that is essentially space heating and domestic hot water), and the second is gas consumers with demand for high-temperature heat (process heat).

For current gas consumers with a demand for low-temperature heat, the basic principle conceived is the substitution of gas, but, depending on the heat demand density (in particular in a future context), by different solutions: if located near the current central district heating network, connection to it. If the distance to the central district heating network is too far, establishment and connection to a local heating network instead (islands of district heating, or “nahwärmenetz”, as we saw conceived also by Munich above). The idea is further that, if and where possible, all local excess and renewable heat resources, should be exploited and used in these networks. In areas not in vicinity neither to central or local networks, the use of decentralised heat pumps or biomass is suggested, as principally outlined in Figure 44. For current gas consumers with demand for high-temperature heat, the corresponding basic principle is to switch to electricity as far as possible, and if and where electrification is not possible in the future, here is where the use of renewable gasses should be prioritised.

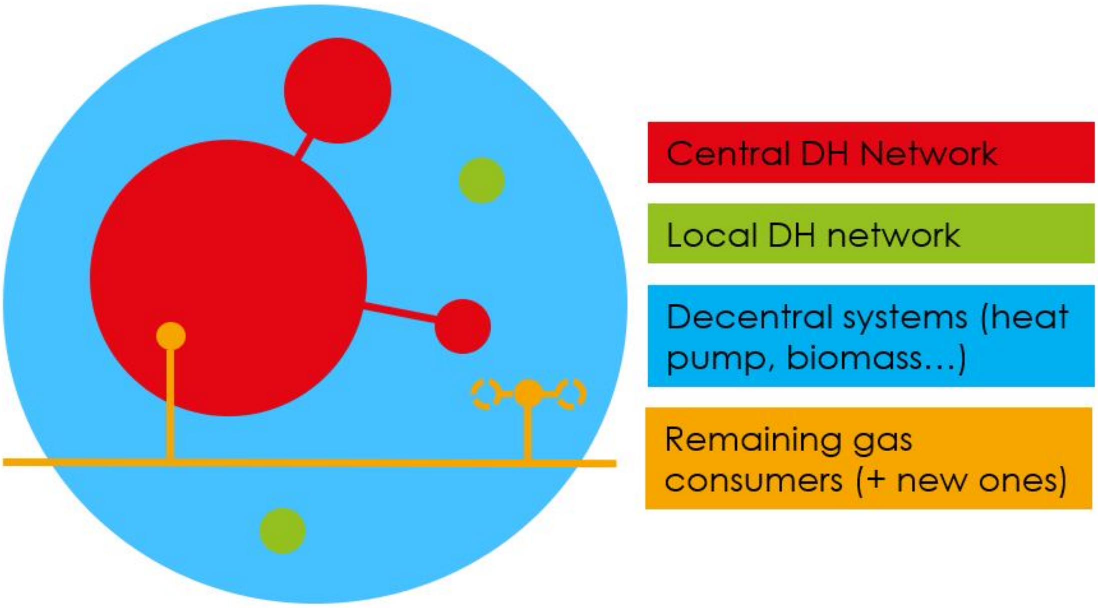

FIGURE 44. ILLUSTRATION OF SPATIAL PRINCIPLE BY WHICH TO DETERMINE TYPE OF HEAT SUPPLY IN VIENNA.

6.2. Draft recommendations: Vienna

As a first reflexion, the great work already performed by the local working group in Vienna can only be applauded. Keep it up, and continue the knowledge build-up, the mapping of local heat resources (as exemplified in Figure 45), and the development of decarbonisation concepts for a heating and cooling sector in need of solid transition strategies for the future. A few draft recommendations at this stage may be a comment on densification of heat demands, which might not be a feasible option in an already very dense city centre, but which likely can be a valuable concept in the outer city districts. Viable approaches whereby to the increase connection rates to the current district heating system also appear as important. Take a look locally also for the biomass and the biomass-based fuels potential! Finally, regarding the peak load issue: What is the realistic potential for peak load shaving by use of large-scale seasonal thermal storages integrated into the district heating system?

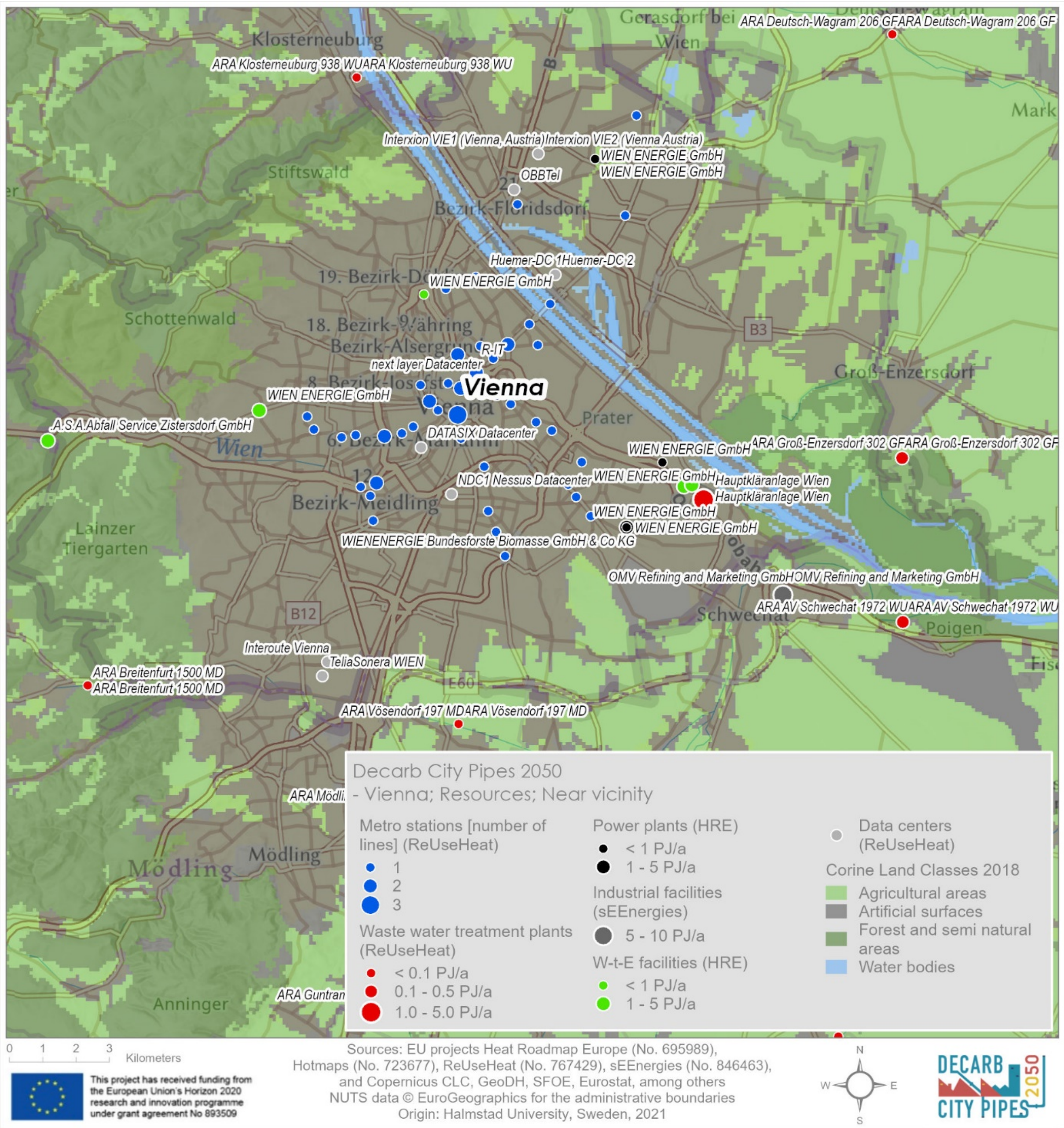

FIGURE 45. EXAMPLES OF HEAT RESOURCES IN VIENNA AND ITS NEAR VICINITY. SOURCES: [9, 12, 13, 28].

6.3. Responses to Vienna LWG questions

The aim of this section is to answer the posed two questions by the local working group of Vienna. Each of the questions is answered in a short and straightforward fashion, which is followed by a more detailed discussion of all the issues that should be considered.

6.3.1. Q1: Parameters for deciding to extend DHC grid

The single most important parameter for deciding to develop or not district heating in a given area is the ground heat density, i.e., the amount of heat per unit of ground area (heat demand density, also known as physical suitability). Although there is not a specific threshold that can determine the direct feasibility since many parameters come into play, a value of 500 MWh/ha (1800 GJ/ha) may be used as a rule of thumb (in countries with highly competitive district heating systems, this value may be as low 200 MWh/ha (720 GJ/ha)).

- Under which conditions (in which areas) is DH always the best option?
  - In city areas with high building density, district heating is very likely to be the most cost-effective means to achieve a decarbonised heat supply. Areas with a heat density over 500 MWh/ha.
- Under which conditions (in which areas) is it most likely never a good option?
  - Sparse areas with highly efficient buildings are very likely to be prohibitively expensive to be supplied by district heating. Individual solutions are bound to be the best alternative. Areas with a ground heat density below 200 MWh/ha.
- Under which conditions/parameters is DHC potentially a good option to be explored?
  - Areas with intermediate heat densities ranging from 200 MWh/ha to 500 MWh/ha, depending on the cost of the centralised heat supply, the installation cost of district heating pipes in sparse areas, and the cost of the alternative heat supply options.

The optimal heat supply option is dependent on the cost of the centralized and individual supply options. Ideally these costs should be assessed at the energy system level in order to take into account the full extent of their impact. For instance, the deployment of a few heat pumps is bound not to have a substantial effect on the electricity grid, but a massive substitution of gas boilers by heat pumps is likely to require a grid reinforcement and the construction or maintenance of back-up electricity generation units, which would be idle most of the time.

This principle should also be applied at the city level to the largest extent the city's powers allows. A local example of the case presented before is the current situation in the city of Helsingborg in Sweden, where the transmission and distribution electricity grids are under pressure during the winter's cold spells due to the significant development of heat pumps in the latter years.

Once the societal optimum has been identified, its attainment also needs to take into account the minimum cost option for the individual in the current boundary conditions. If the right incentives are not in place, the individual search for the minimum cost may well lead to solutions which are far from the societal optima. A blend of regulatory and economic incentives should then be implemented so as to align both optima.

The recent reduction of the electricity tax in Denmark illustrates this problem. The State's aim for substituting oil boilers by heat pumps has led to a drastic reduction of electricity taxes for heat production. Whilst this favour the removal of oil boilers as heat pumps have become more competitive, it also makes heat pumps to have a similar cost to district heating, which may incite some households to leave the centralised heat supply. The installation of these apparatuses may bring some individuals an economic benefit, but it could also start a spiral in which households leave district heating systems, why these become proportionally more expensive, which in turn leads to more households abandoning district heating networks. The concomitant effect is that the electricity grid also becomes more expensive and the spot market price more temperature dependent, two costs that are passed to all electricity consumers.

The project Heat Roadmap Europe has carried out Energy System analysis for various European countries and concluded that heat pumps are the most cost-effective solution in rural and low-density areas whereas district heating can bring system-wide benefits in dense urban areas.

The next section deals with the cost of centralised heat supply and its main drivers. Even though the establishment of district heating entails a large number of components, the main outlays are three: production, distribution, and house connections. The sum of these three needs to be cheaper than the cost of the individual solution, as illustrated in Figure 46.

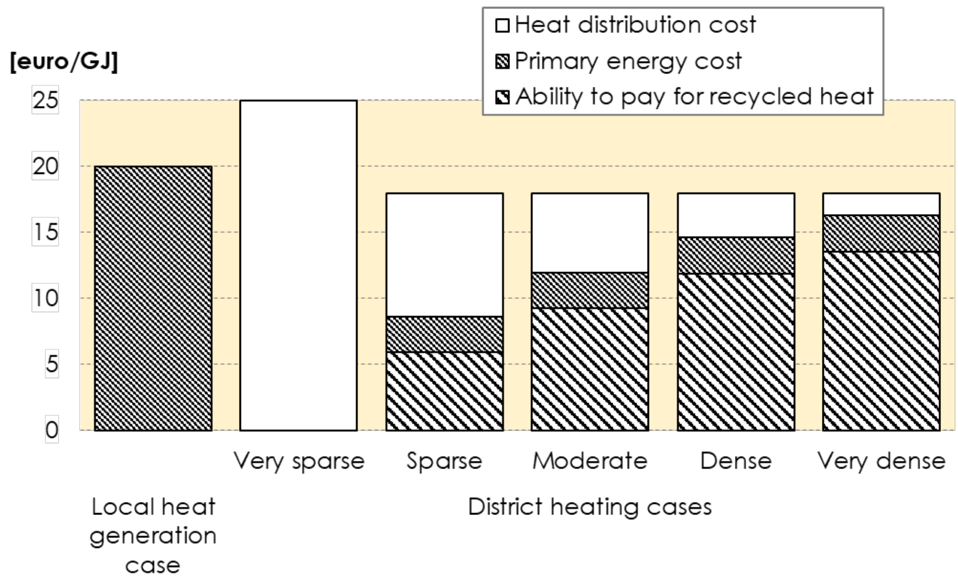

FIGURE 46. COST OF LOCAL HEAT GENERATION AND DISTRICT HEATING DEPENDING ON HEAT DENSITY. ELABORATED ON THE BASIS OF SOURCE: [21].

Firstly, the cost of heat production generally has some economies-of-scale, since larger production units present lower unit costs although these have generally decreased over the last century [30]. An example of economies of scale in production is the unit cost for solar district heating depicted in Figure 47, which demonstrates that large ground-mounted solar collectors are considerably cheaper than individual installations. Another example of a source that becomes economic with size is a distant heat supply whose transport cost to the city decreases the more heat is transported. In this sense, it might be justified to expand a district heating network into a more expensive area, if this increase in demand allows to access a cheap heat source, which leads to an overall more economic heat supply.

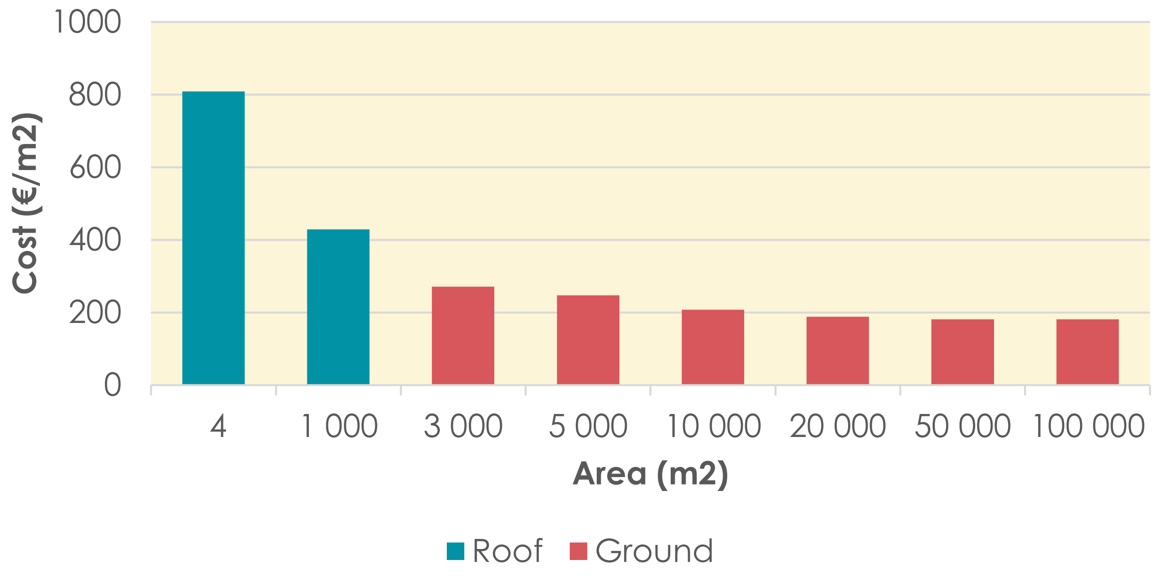

FIGURE 47. UNIT COST OF SOLAR DISTRICT HEATING AS FUNCTION OF COST. SOURCE: [67].

However, economies-of-scale are not the main driver of district heating nowadays, but rather the possibility of using sources that otherwise would not be feasible, i.e., economies-of-scope [30]. There are many heat sources, which cannot be utilised without district heating such as deep geothermal, industrial waste heat, incineration, cogeneration, large-scale solar thermal or large heat pumps.

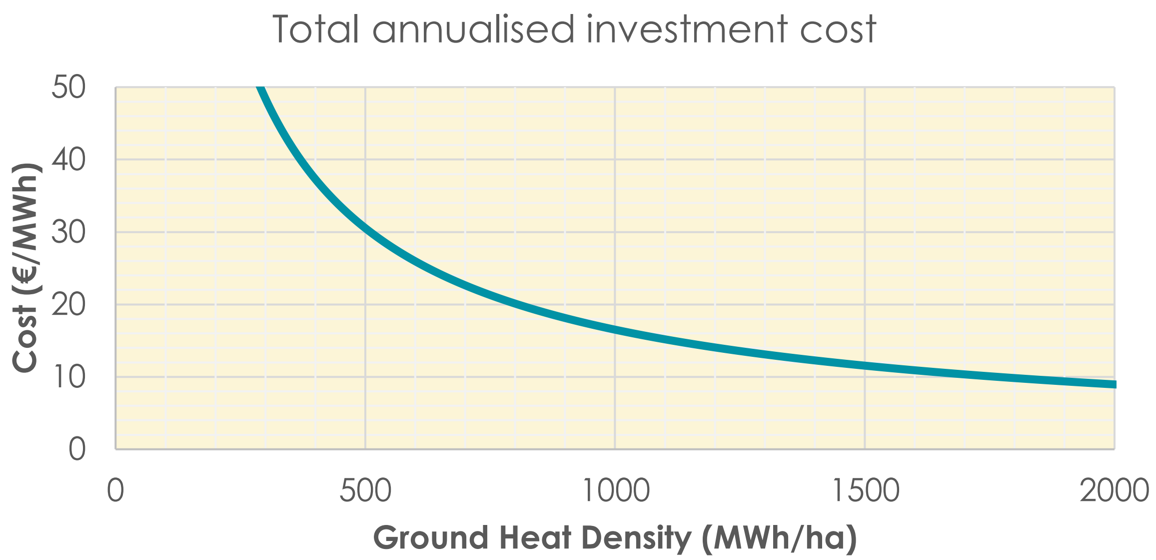

FIGURE 48. COST OF THE DISTRICT HEATING NETWORK (DISTRIBUTION AND SERVICE PIPES) AS FUNCTION OF THE GROUND HEAT DENSITY.

Secondly, the cost of distributing heat in district heating networks is determined to a large extent by the ground heat density, this is, the heat demand per unit of ground area, q_L. Areas with higher heat densities have lower costs because of two reasons:

- Firstly, a larger amount of heat can be supplied without increasing the pipe length.
- Secondly, larger pipes are cheaper proportionally to the heat they are able to deliver.

Thus, and unlike production, heat distribution presents significant economies-of-scale, or more accurately *Economies-of-density*. Other parameters such as the system temperatures or the installation cost of district heating pipes play a role too, but they are of lesser importance. In Figure 48 it has been depicted the cost of district heat distribution as function of the ground heat density of the area and it can be clearly appreciated that the cost decreases substantially from over 50 €/MWh for a heat density of 200 MWh/ha to less than 10 €/MWh for a heat density of 2000 MWh/ha.

The ground heat density can be expressed as the product of the building density, ε, and the specific heat demand per square meter of floor area, q, as indicated in this equation:

$$q_L = q \cdot \varepsilon$$

In principle, two areas with very different urban fabrics could have the same heat densities, and hence, similar distribution costs. For instance, an area which has single-family buildings with a specific heat demand of 150 kWh/m^2_{floor} and where the building density is 3 333 m^2_{floor} per hectare, would present a ground heat density of 50 kWh/m^2_{ground} (150 kWh/m^2_{floor} · 0.3333 m^2_{floor}/m^2_{ground} = 50 kWh/m^2_{ground} = 500 MWh/ha). Another city area built in the *Passivhaus* standard with a specific heat demand of 35 kWh/m^2_{floor} but simultaneously higher building density of 14 285 m^2_{floor} per hectare would also deliver a ground heat density of 50 kWh/m^2_{ground} (35 kWh/m^2_{floor} · 1.43 m^2_{floor}/m^2_{ground} = 50 kWh/m^2_{ground} = 500 MWh/ha). These two areas have the same ground heat density and therefore, they would have a similar pipe network cost of around 30 €/MWh. A clear conclusion may be drawn from this, low energy buildings can be economically supplied by district heating as long as the building density is high enough.

The higher cost of building district heating in lower density areas makes that these systems are only feasible in these areas if the cost of the individual supply is rather high. This is generally not the case, except for the noteworthy exception of Denmark, where the supply of detached houses by district heating is widespread. High taxes on fossil fuels and electricity made that the cost of an individual natural gas boiler, oil boiler or heat pump were rather expensive and thus, it allowed district heating systems to expand in these zones. Other factors such as a mature market with relatively competitive installation costs of district heating pipes have also contributed to the current market share above 50%.

The third element that comes into play is delivery, this is, the interface between the district heating system and the internal heating and district heating system. From a purely installation cost perspective, building substations could be preferred as they have lower unit cost. However, individual substations present other advantages, which will be more prominent in the future and research has consistently recommended their utilization for moving towards 4th Generation Systems. They allow using lower system temperatures, close monitoring of the heat consumption and detection of errors. In any case, and concerning domestic hot water, instantaneous preparation without storage should be preferred as it enables lower return temperatures without the risk of legionella proliferation.

A measure to reduce the cost of individual district heating substations would be the employment of direct connections for the heating systems. If this approach is taken, the district heating water circulates in the consumers' heating installations and the district heating substations only contains a differential pressure controller. The removal of all other equipment such as circulation pump, expansion tank, and control system, leads to a significant drop in price. For example, an indirect connection unit from Danfoss Redan is 2.5 times more expensive to the public than its direct connection counterpart[36] (if the units are bought in bulk to the manufacturer the price difference will likely be smaller). These units impose however lower pressures in the distribution network since the maximum allowable pressure cannot be higher than the maximum pressure withstood by the consumers' heating systems. This is the case of Denmark, where direct connections are common and the pressure in the distribution networks is frequently limited to 6 or 10 bars. This pressure requirement would unfortunately trigger the utilization of larger pipes or smaller distribution networks (and larger transmission networks), consequently increasing the cost of the pipe network. Therefore, it is necessary to assess which solution is globally the most economic.

6.3.2. Q2: Making DHC "future-proof" / needs of utility

- What models exist (in Sweden?) that can help utilities to make DHC more competitive and a good future-proof option?
- Is time- or temperature-dependent DH tariffs a possibility and how to implement them?

Time or temperature dependent DH rates have been and are employed by many district heating systems. In the following two sections it is addressed the two issues separately, but it must be noted that a combination of them or even a combination of the different solutions is possible.

Regardless the chosen price model, the district heating operator should actively engage with the customers and explain the purpose of these special tariffs and how they can change their behaviour and/or heat systems to reduce their impact.

Research has also shown that the price model needs to be kept reasonably simple and predictable [68]. Furthermore, although advantageous as it will be explained below, consumers find it more difficult to understand flow or heat power rates rather than seasonally differentiated prices [68].

6.3.2.1. Time dependent tariffs

The heat rates should reflect the cost of producing heat, which varies significantly over the year in different time scales.

Firstly, the cost of heat tends to have seasonal variations. On the one hand, it is usually lower in the summer as this is supplied by baseload or solar technologies which have a lower marginal cost (or negligible in the case of solar). On the contrary, heat is more expensive during the winter since technologies with higher marginal costs (but lower investment costs) are employed in these periods.

Without price differentiation, the consumer could decide to purchase its own (individual) heat production unit for base load and purchase from the network only under-priced peak load in detriment to the rest of the network consumers. As an example, the city of Helsingborg in Sweden has the prices of 73, 41 and 10 €/MWh for the winter, mid, and summer seasons, respectively [69]. This price model is represented in the model b of Figure 49.

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[36] A Danfoss Redan Akva Lux II TDv with direct connection has a price of 8.900 DKK whereas a Akva Lux II VXe has a price of 22.400 DKK at the Danish Website VVS-Shoppen (1, 2).

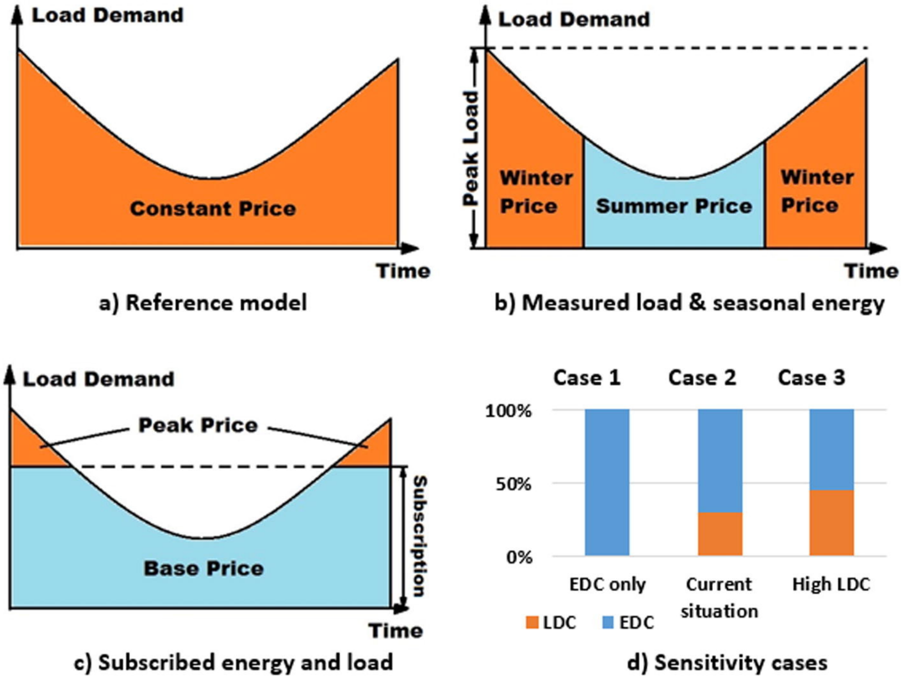

FIGURE 49. DIFFERENT MODELS FOR SEASONAL PRICING. SOURCE: [70]

Lower summer heat rates could also create an incentive for large consumers to utilise district heat for cooling by means of absorption chillers.

Another way of reflecting the cost for base and peak load in the heat rates would be to establish different prices for different loads. The lowest load would be charged reflecting the cost of baseload whereas the subsequent heat demand would be charged reflecting the production cost of peak load. This price model is represented in the model c of Figure 49.

The two aforementioned seasonal models can also be respectively represented by the following two equations :

$$C_E = \sum_{i=1}^{8760} P_i \cdot E_i$$

And :

$$C_E = \sum_{i=1}^{8760} P_{base} \cdot min\,(E_i, E_{base}) + \sum_{i=1}^{8760} P_{peak} \cdot min\,(E_i - E_{base}, 0)$$

Where:

- C_E is the cost of the heat.
- E_i is the energy demanded in the hour i.
- P_i is the seasonal price in the hour i.
- P_{base} is the price for the base load.
- P_{peak} is the price for the peak load.
- E_{base} is the threshold above which the energy demand is considered to be supplied by peak load units.

Secondly, the cost of heat may also have significant variations on an hourly basis and hence, this could be reflected in the rates applied to the heat consumed during different hours of the day. For instance, buildings in Italy are legally obliged to implement night set-backs and, therefore, district heating systems in Italy present drastic variations in the heat load between day and night [71]. In order to incentivise the consumption of heat at night, some district heating systems have set up day and night tariffs; this is the case of Turin, where the prices of heat during the night and day are respectively 29 €/MWh and 51 €/MWh [72] [37].

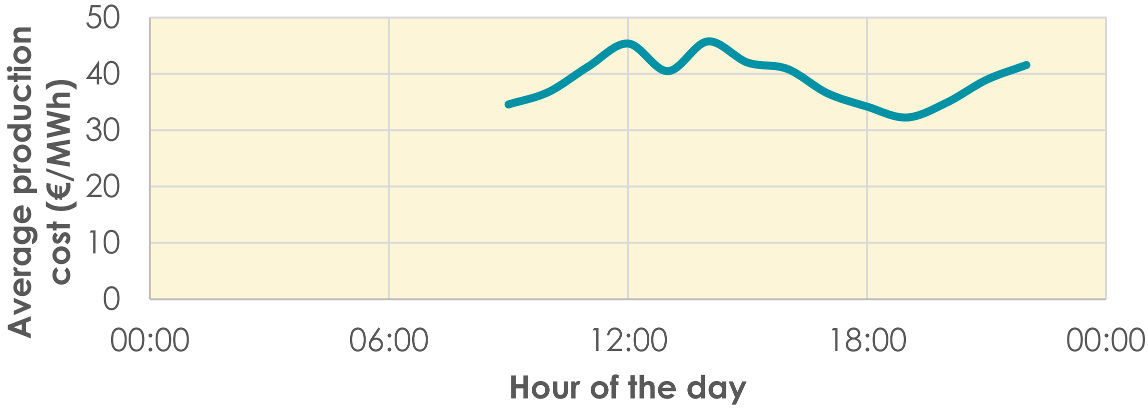

FIGURE 50. HOURLY AVERAGE PRODUCTION COST IN THE CITY OF AARHUS THE 22-09-2019[38]. SOURCE: [73].

Besides these differentiated tariffs in two periods, it would also be possible to apply hourly prices depending on the cost of heat production. For instance, some district heating companies provide their hourly production cost even though they do not translate these to their customers; this is the case of the city of Aarhus (Denmark), whose hourly average production costs for the 22nd of September of 2019 are depicted in Figure 50. Furthermore, hourly prices have been implemented in electricity tariffs reflecting the spot market and/or varying network fees; this is the case of the Spanish PVPC, exemplified in Figure 51.

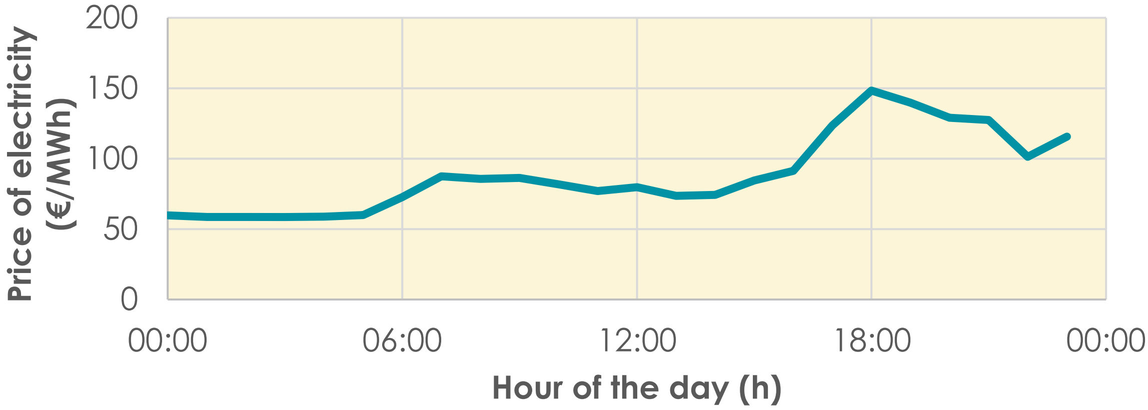

FIGURE 51. HOURLY ELECTRICITY PRICES[39] FOR DOMESTIC CONSUMERS IN SPAIN THE 10TH OF FEBRUARY OF 2021. SOURCE: [52].

[37] Excluding VAT.
[38] These prices have been converted into Euros assuming an exchange rate of 7.45 €/MWh.
[39] The prices do not include the Electricity Tax (5%) or the VAT (21%).

6.3.2.2. Temperature dependent tariffs

It is possible to implement temperature-dependent tariffs in multiple ways but here we will limit ourselves to three different solutions, whereof the first two address temperatures directly and the last one behaviour that have negative influences on the district heating temperatures.

6.3.2.2.1. Incentive tariff

The consumer may receive a penalization or bonus depending on the return temperature. This may be expressed in relative terms with respect to the heat cost or through a price per unit of energy delivered. Examples of the first are the district heating systems of the Danish cities of Viborg[40] and Rønde, where the consumer obtains a 1% or 2% discount of the total invoice per degree below the threshold [75, 76]. The district heating operator of Copenhagen, Hofor, has, on the other hand, established a discount of 4.19 DKK/MWh·°C (equivalent to 0.8%) [77]. Although more complicated set-ups are possible, for instance depending on the supply temperature at the consumer, a simple application could be carried out by means of the following expression:

$$C_T = E \cdot p_e \cdot (1 + (T_r - T_t) \cdot \alpha)$$

Where:

- $\mathrm{C_T}$ is the total cost for the consumer.
- E is the energy delivered.
- p_e is the price per unit of energy.
- T_r is the return temperature.
- T_t is the threshold temperature, below which the consumer is benefited and above which it is penalised.
- α is the penalization rate, according to the previous examples it could range from 0.01 to 0.02.

The incentive tariff may be designed so that it is revenue-neutral, this is, some consumers are penalised, and others are incentivised but, on average, the district heating does not obtain any additional income. In the above equation, the parameter to estimate would be the threshold temperature.

6.3.2.2.2. Flow tariff

A part, or all, of the rate linked to the consumption may be charged as function of the flow circulated through the district heating substation instead of the energy demand. This was the tradition in many district heating systems before the advent of the modern heat meters and it has the benefit of creating a natural incentive to reduce the return temperature as much as possible.

In the following formula, it is expressed the volume flow, V, for a given energy amount, E, and the supply and return temperatures (T_s and T_r respectively):

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[40] Further information on the city of Viborg's incentive tariff may be obtained from 74.Diget, T., *Motivation Tariff - The key to a low temperature district heating network.*, in *Hot & Cool Magazine*. 2019: Frederiksberg. p. 19-22..

$$V = \frac{1}{c_p \cdot \rho} \cdot \frac{E}{T_s - T_r}$$

If the consumer needs a certain amount of heat to warm up its home, the lower the return temperature, the lower the flow, and hence, the lower the cost for the consumer. Currently the district heating system of Aalborg employs this system [78].

An example of this system is also given below in Table 8, with two consumers with the same energy demand but different return temperatures. With an energy rate the two consumers would experience the same cost regardless of their temperature performance. However, the consumer with a lower return temperature is benefited when a flow rate is utilised.

TABLE 8. COST OF HEAT SUPPLY WITH ENERGY AND FLOW RATES.

	Consumer A	Consumer B
Heat demand	8 000 kWh	8 000 kWh
Supply Temperature	80°C	80°C
Return Temperature	60°C	40°C
Flow	344 m^3	230 m^3
Cost with Energy rate (50 €/MWh)	400 €	400 €
Cost with Flow rate (1.742 €/m^3)[41]	600 €	300 €

A flow rate is equivalent to an incentive tariff with variable penalization rate (α in the above equation for incentive tariff) depending on the temperature difference as it can be appreciated in Figure 52.

Moreover, and on the contrary to the incentive tariff presented before, the penalization for higher return temperatures than the threshold is higher than the benefit for lower temperatures than the threshold.

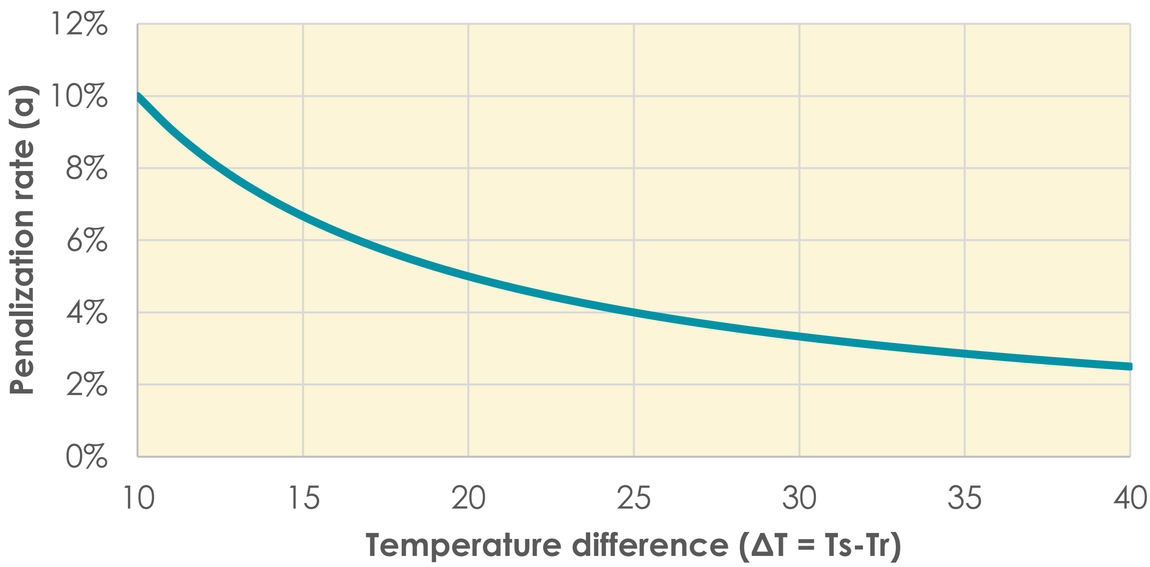

FIGURE 52. PENALIZATION WITH A FLOW RATE.

[41] This price is equivalent to an energy price of 50 €/MWh with a cooling of 30°C.

6.3.2.2.3. Maximum capacity rate

This tariff aims to prevent consumers from using night setbacks or an on-off setting of the heating system. This type of behaviour offers some benefits in poorly insulated houses since it brings about a reduction of the heat demand, but it has a negative impact on the return temperature and heat power. From a global perspective, the system cost reduction that lower system temperatures triggers is likely higher than the reduction of cost because of a lower heat consumption.

Importantly, the period in which the maximum capacity is determined needs to be carefully considered. Due to the seasonal heating variation, it would not be completely fair if the maximum capacity is calculated during the entire year. A shorter period, such as a week or a day, would provide a much more realistic indicator of the consumers' behaviour. Furthermore, the period cannot be too small since the demands from the domestic hot water consumption would start to alter the results[42].

As an example of this, Figure 53 and Figure 54 show the heat demand resulting from applying two heating schedules to the same dwelling, one with continuous operation and one with evening heating for seven days. As it can be appreciated, the continuous operation requires a lower heat power and lower temperatures (and hence lower flow rates).

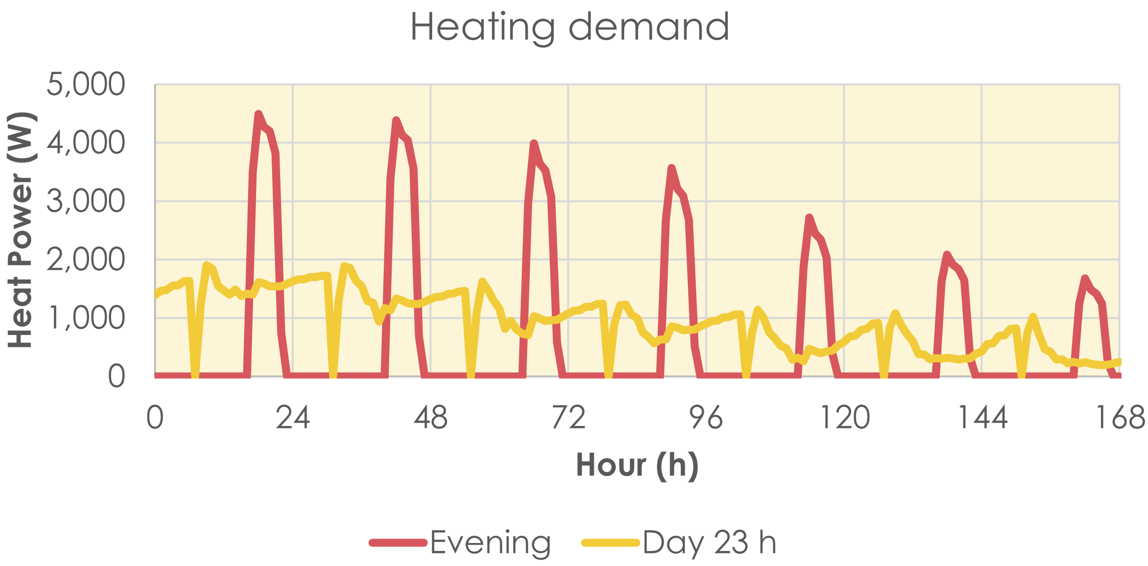

FIGURE 53. HEATING DEMAND OF A DWELLING DURING A WEEK WITH TWO DIFFERENT SCHEDULES.

In practice, the total tariff is divided into two parts, one that charges the energy/volume consumed and the second one that charges the maximum heat power/flow demanded:

$$C_T = E \cdot p_e + \dot{E}_m \cdot p_{\dot{e}_m}$$

Where:

- E is the energy delivered.
- p_e is the price of heat.

[42] Domestic Hot Water preparation requires heat powers and flows considerably higher than heating, but they last for very short times. Therefore, if the heat consumption is averaged in two or three hours the impact of DHW in the load will be negligible.

- $\dot{E}_m$ is the maximum heat power demanded.
- $p_{\dot{e}_m}$ is the price of the heat power.

In this particular case and during this one-week period, the application of a flow rate provides an incentive high enough to avoid the night set-back behaviour since the flow of this latter option is higher, as it is presented in Table 9. However, this is not the case for the entire year as the flow for the continuous operation is 32% higher (than for the discontinuous mode) and the heat demand is 71% higher.

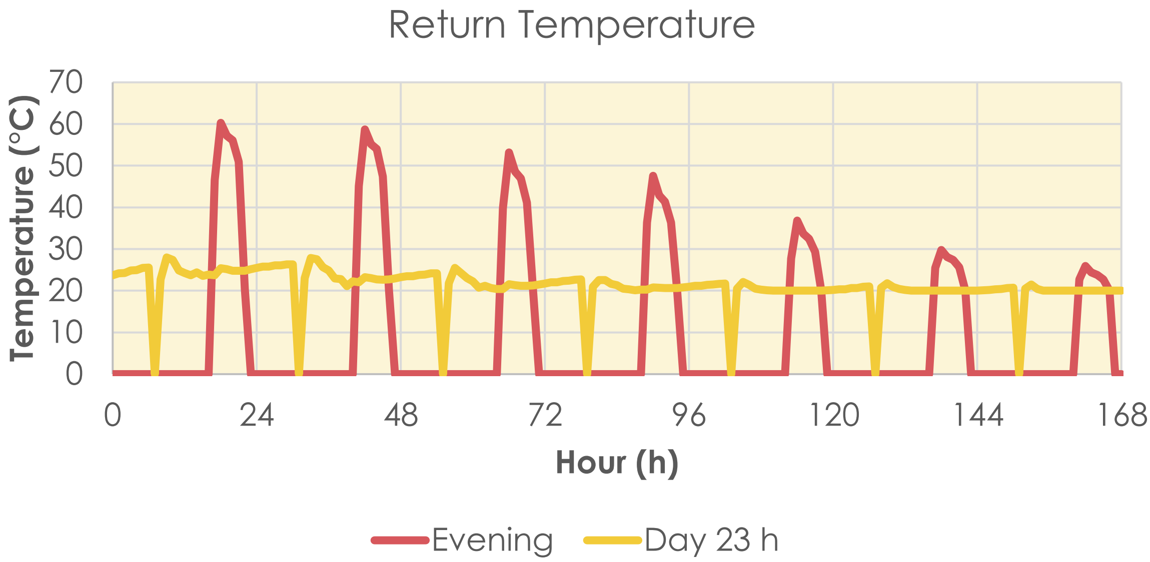

FIGURE 54. RETURN TEMPERATURE FROM THE HEATING SYSTEM OF A DWELLING WITH TWO DIFFERENT SCHEDULES.

In this specific case, if the price of energy were 30 €/MWh, the price of power 250 €/MW·day, and the peak power were calculated on a daily basis, the cost for the two consumers would be roughly the same (around 110 €), and the average heat price for the consumer without night set-back would be 50 €/MWh.

TABLE 9. RESULTS OF DIFFERENT HEATING SCHEDULES.

	Evening schedule (with night set-back)	All-day schedule (without night set-back)
Energy	103 kWh	157 kWh
Volume	2.656 m3	2.367 m3
Return Temperature	46°C	23°C
Maximum Heat Power	4500 W	1904 W

6.3.2.2.4. Equivalence between Flow Rate and Energy Incentive Tariff

A flow tariff may be considered as an incentive tariff with a penalization/bonus depending on the temperature difference.

First, it is necessary to determine the equivalence between a flow rate and an energy rate. In order to do that, it is necessary to assume a threshold return temperature for which both rates are equivalent:

$$C_F = C_E \rightarrow p_e \cdot E = p_f \cdot V$$

$$p_e \cdot V \cdot \rho \cdot c_p \cdot (T_s - T_t) = p_f \cdot V$$

$$p_e \cdot \rho \cdot c_p \cdot (T_s - T_t) = p_f$$

The second step is to apply the former expression to determine the cost of the heat supply:

$$C_F = p_f \cdot V = p_e \cdot \rho \cdot c_p \cdot (T_s - T_t) \cdot V$$

$$C_F = p_f \cdot V = p_e \cdot \rho \cdot c_p \cdot V \cdot [(T_s - T_r) + (T_r - T_t)]$$

$$C_F = p_e \cdot \rho \cdot c_p \cdot V \cdot (T_s - T_r) \cdot \left[1 + \frac{1}{(T_s - T_r)} \cdot (T_r - T_t)\right]$$

$$C_F = p_e \cdot E \cdot \left[1 + \frac{1}{(T_s - T_r)} \cdot (T_r - T_t)\right]$$

This expression can be rewritten in a similar way to the energy rate with a penalization:

$$C_F = p_e \cdot E \cdot [1 + \alpha \cdot (T_r - T_t)]$$

Where α is the penalization/bonus, which unlike the pure energy rate is variable depending on the supply and return temperatures:

$$\alpha = \frac{1}{(T_s - T_r)}$$

By these theoretical concepts and relationships regarding an equivalence between tariffs based on flow rate and energy incentive, which we leave for the reader to digest and ponder without further comment or elaboration at this stage, we believe that answers have been given to the two explicit questions posed by the local working group in the city of Vienna. As we now turn to the last of the six cities presented in this report, Winterthur, we hope that these answers may be of value also for the other project cities.

7. Winterthur

For the Swiss city of Winterthur, the sixth and final city to be presented in this report, a city located in the greater Zürich region with a population of 110 thousand, the authors have not had access to data by the same extent as for the other cities. The reason for this is that Switzerland were excluded from the study scope in the most frequently used sources for the overview maps presented in this report, the Heat Roadmap Europe [9] and the sEEnergies [13] projects. Luckily, the local working group in Winterthur, which is led by the Department of Construction at the City of Winterthur, has high-quality statistics and data of their own. Still, for stylistic coherence and comparison, the heat demand density of Winterthur is presented in Figure 55, where, in this case, data from the Swiss Federal Office of Energy was used (note: unclear whether this data refers to final consumption or end use demands).

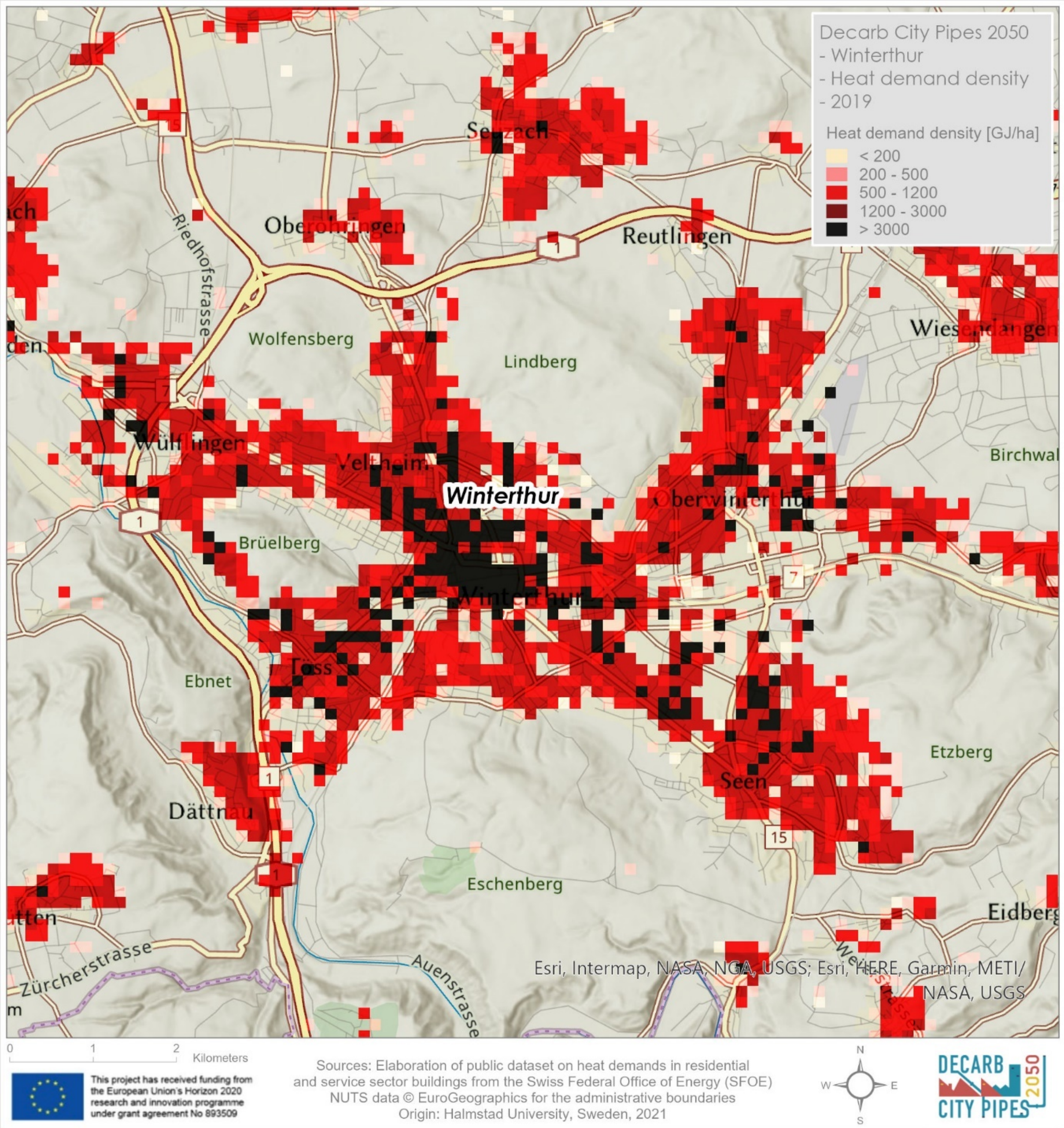

FIGURE 55. MAP OF HEAT DEMAND DENSITY BY HECTARES IN THE CITY OF WINTERTHUR. SOURCE:[79].

The local working group in Winterthur is organised by an institutional design which consists of two main constellations: a core group ("fachliche Kerngruppe") of about 10 people and a political group ("Begleitgruppe", or support group), not further specified. The group meets once a month, or on demand if called upon, and assembles representatives from the city utility (the Stadtwerk Winterthur), from the city administration building permit department and its environment and health department, as well as external partners. A key topic for discussions have, already from the start, been the extension of the existing district heating network, which, as can be seen in Figure 56, represents an 18% heat market share (220 GWh) in the current year city energy demand for heating and cooling purposes. In this respect, the LWG has been working (as part of Phase 1 activities) with interviews with stakeholders (e.g. utility and DSO's) as well as data collection regarding the current situation.

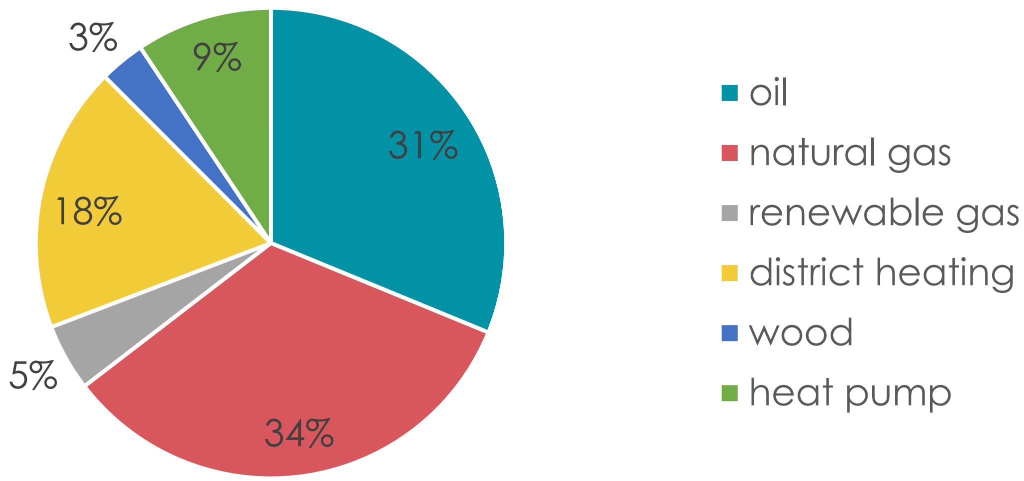

FIGURE 56. CURRENT YEAR (2019) FINAL ENERGY DEMAND FOR HEATING AND COOLING IN THE CITY OF WINTERTHUR BY TYPE OF HEAT SUPPLY.

According to information shared by the local working group in Winterthur, the total current year final energy demand of all heated buildings in the city amounted in total to 1.2 terawatt hours in the year 2019. The total towards which the relative shares depicted in Figure 56 refer is this annual volume, of which oil constituted some 370 GWh (31 %), natural gas approximately 400 GWh (34 %), renewable gasses an additional 60 GWh (5%), biomass (wood) 40 GWh (3 %), and heat pumps a final 110 GWh (9%).

The district heating supply is also well-documented, which can be seen in the map presented in Figure 57. From this map it is clear that the district heating system already today utilises excess heat from a waste incinerator as well as from at least one waste water treatment plant. Other than that, a large number of biomass-fuelled boilers in the 100 kW-range and above are distributed across the city but it is not discernible from the shared information whether these are operated in cogeneration or heat-only generation mode. An added value from the map in Figure 57 in this context, or rather from the capability of a local working group to be able to provide it, is the opportunity to illustrate and emphasise the benefits of spatial mapping and a clear, detailed, and comprehensive cartographic overview in association with strategic heat planning. It is, in fact, at heart of the matter!

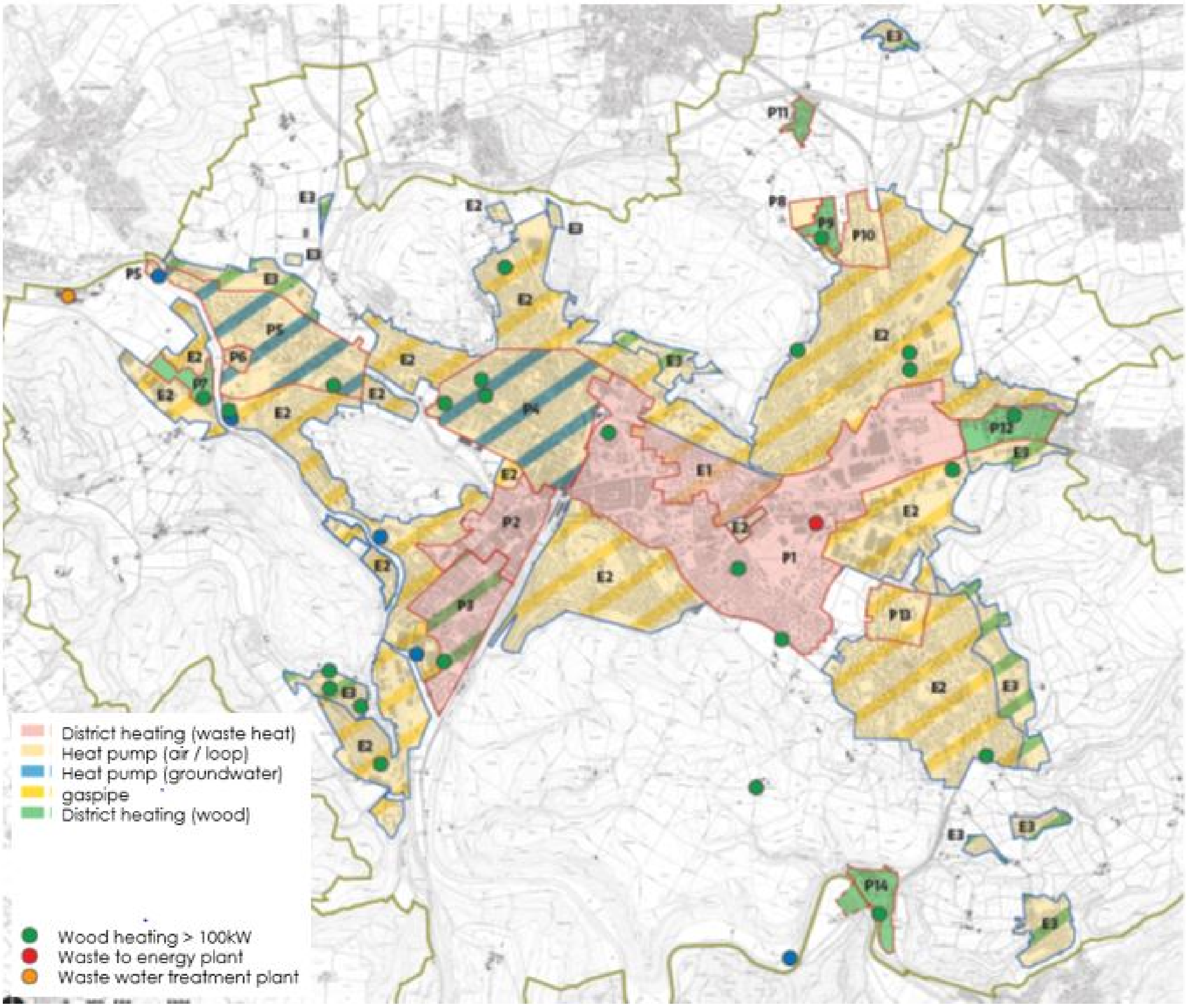

FIGURE 57. THE CURRENT ENERGY PLAN IN THE CITY OF WINTERTHUR WITH SPECIFICATION OF HEAT SUPPLIES BY DIFFERENT CITY DISTRICTS (COPY OF PRESENTATION SLIDE).

7.1. Heating and cooling outlook 2050: Winterthur

The city of Winterthur has, as all other project cities, adopted future targets for the reduction of greenhouse gas emissions from heating and cooling sector activities. In terms of per-capita carbon dioxide equivalent emissions, the goal for Winterthur translates into a cap at 0.3 tonnes by 2035, which is similar to the targets mentioned for the city if Munich above. Since current corresponding emissions are stated at some 1.8 tonnes, quite drastic means and measures may have to be accepted to reach the targets. For Winterthur, the 2035 goal is to no more use oil for any purposes whatsoever, to use no natural gas for heating purposes at all, but to use smaller amounts for industrial purposes (10% natural gas and 30% renewable gasses relative to current levels of natural gas use).

The total anticipated final energy demand of all heated buildings in Winterthur for the year 2035 is stated at 1.1 terawatt hours, which indicates an expected total heat demand reduction of only 8% during the stipulated period (2019 to 2035). By relative shares, as presented in Figure 58, this final energy demand for heating and cooling in 2035 will consist of zero oil, 50 GWh of natural gas (5 %), 150 GWh of renewable gas (14%), 500 GWh of district heating (46 %), 50 GWh of Wood (5 %), and 330 GWh of heat pumps (30%).

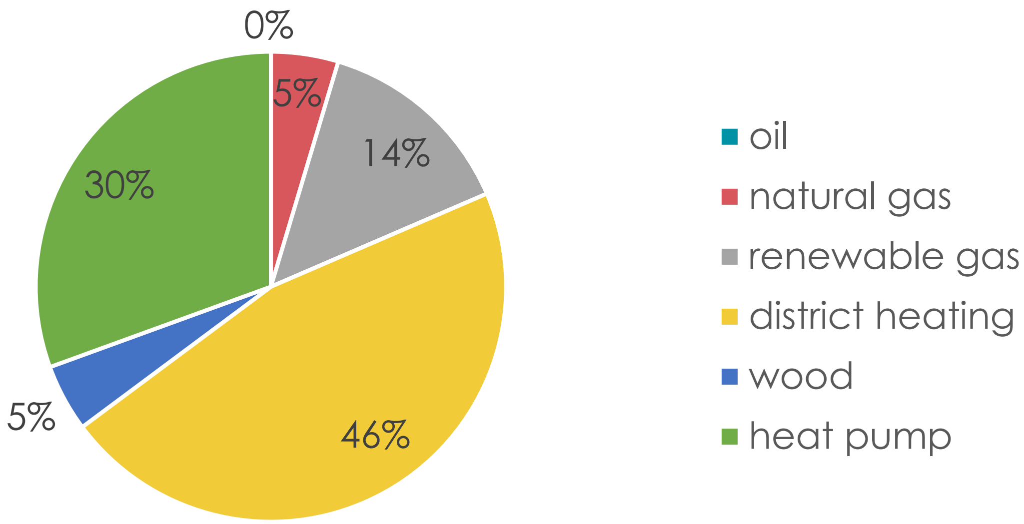

FIGURE 58. FUTURE YEAR (2035) FINAL ENERGY DEMAND FOR HEATING AND COOLING IN THE CITY OF WINTERTHUR BY TYPE OF HEAT SUPPLY.

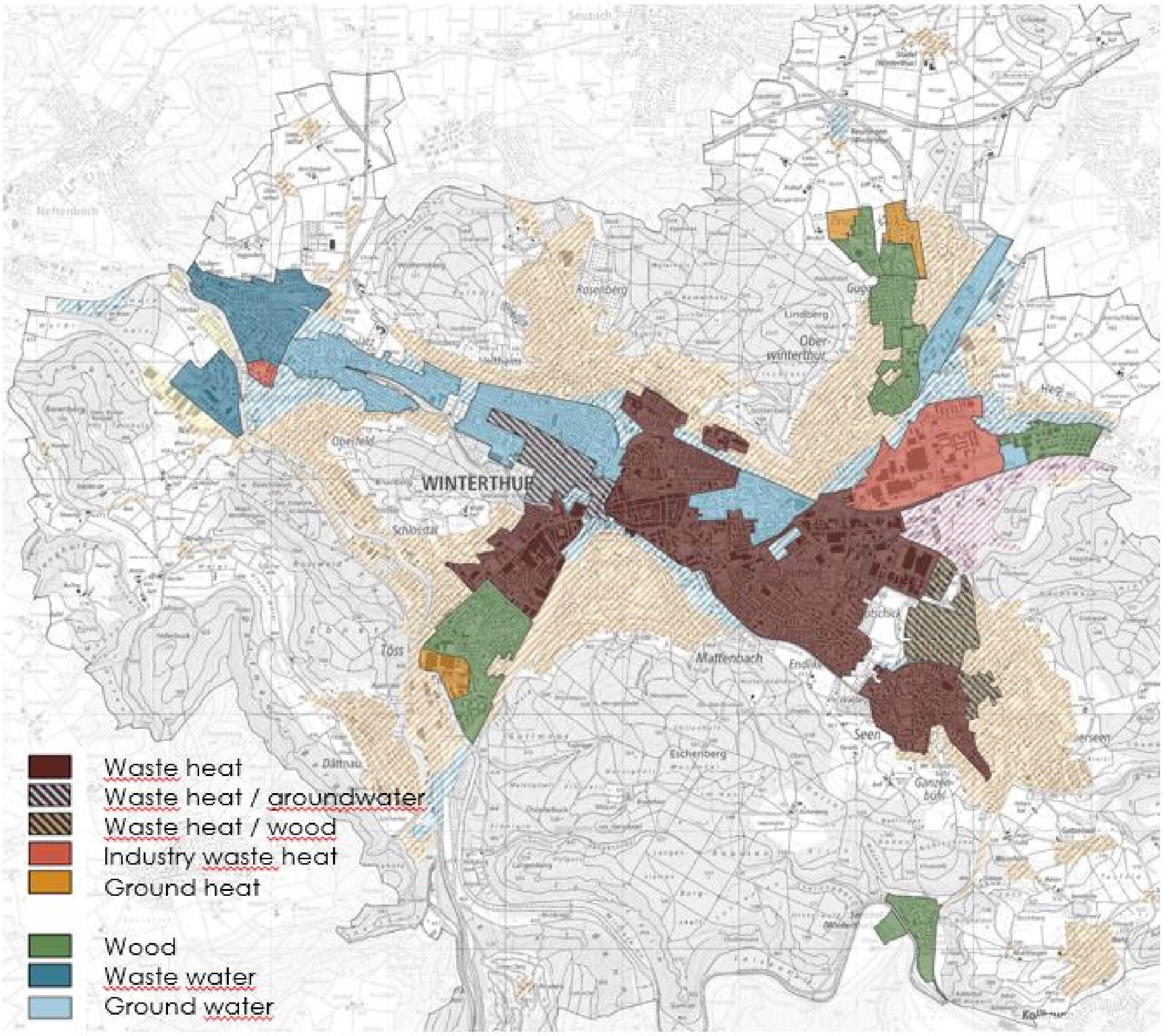

FIGURE 59. CITY MAP WITH ANTICIPATED HEAT SOURCES FOR DISTRICT HEATING IN WINTERTHUR BY 2035.

7.2. Draft recommendations: Winterthur

By studying the design and supply sources used in the anticipated future district heating system in Winterthur, as presented in the map of Figure 59, which was prepared by the local working group in Winterthur as part of their milestone 2 heating and cooling supply outlook 2050, one can only conclude that this city indeed has a plan, and a well-conceived one too! We see that the city will expand its district heating system from 18% to 46% in relative terms, or from 200 GWh to 500 GWh a year in absolute terms, which in itself represents a progressive and quite radical step in pursuit of a realistic solution to the problem. We see further that the city will utilise excess heat from various sources, such as industries and waste water treatment plants, as well as biomass and large-scale heat pump, in order to decarbonise this district heating system.

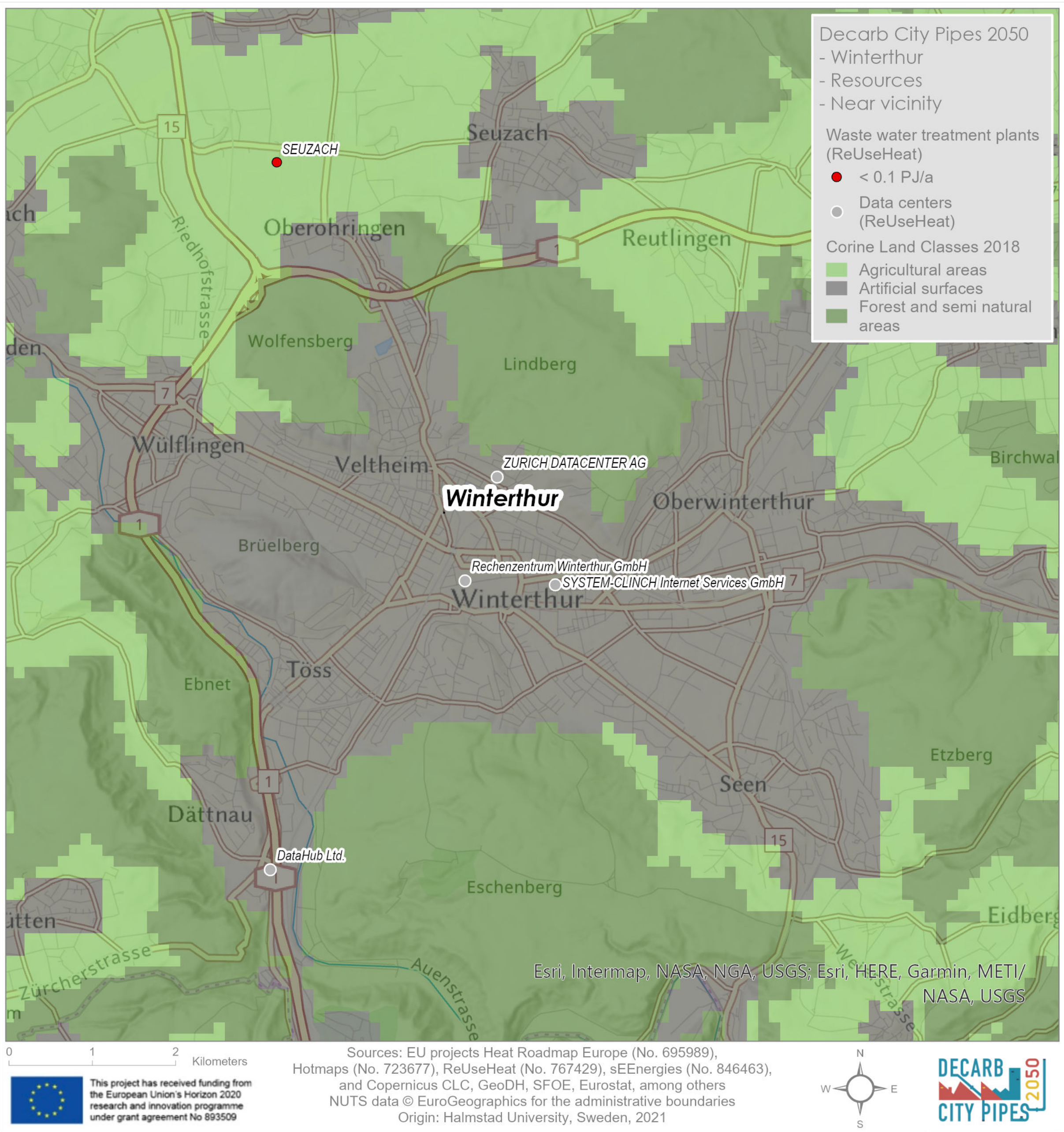

FIGURE 60. EXAMPLES OF HEAT RESOURCES IN WINTERTHUR AND ITS NEAR VICINITY (NOTE, INCOMPLETE DATA COVERAGE). SOURCES: [12, 28].

As for draft recommendations, first, just to maintain equal representation, a corresponding heat resource map for the city of Winterthur, as for the other project cities, is presented in Figure 60 albeit this map suffers greatly from insufficient access to data. Still, one of the few datasets with Swiss coverage available to the authors, that of data centres from the ReUseHeat project [12], might at least be of suggestive value as for additional resources of low-temperature excess heat to be recovered in the future city.

A second reflection is that concerning the level of heat demand reduction anticipated for the future reference year. Perhaps our calculations are misleading, but the quota of 1.1 terawatt hours (final demand in 2035) by 1.2 terawatt hours (final demand in 2019) gives 0.917, which, if subtracted from one, gives 0.083, and thus, suggests a heat demand reduction in relative terms of 8.3%. There are likely good reasons for this anticipated level, but a draft recommendation would be to still revisit this number and look into the issue again. Isn’t there more to do in Winterthur regarding heat savings in buildings?

A third comment may be that, as in particular for Vienna, Munich, and Rotterdam above, about how to obtain lower distribution temperatures in the current district heating system. Is this part of the plan? If so, by what measures and steps will it be achieved? It is perhaps excessive to repeat it here, but the obtainment of lower operational temperatures in the future network is essential for the realisation of direct low-temperature excess heat recoveries, without having to involve heat pumps in such recoveries.

Finally, what about deep geothermal in Winterthur? Did you consider this option at all? Figure 34 above doesn’t indicate terrific opportunities, but not terrible ones either.

8. Summary

This report presents draft recommendations in response to the first initiatives and insights among six local working groups (LWG's) in six European cities 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), all of which are partners in the EU Horizon 2020 project *Decarb City Pipes 2050 - Transition roadmaps to energy efficient, zero-carbon urban heating and cooling*. The overall objective of the 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, which is supported among other things by capacity building activities and peer-to-peer exchanges.

The presented draft recommendations are thought to be supportive and directional for the partner cities, but also to provide insights, ideas, and suggestions of general interest. Apart from city-specific sections, structured similarly for each city with overview descriptions of the current situation and the respective future outlooks, the report also includes an extended introductory section and two in-depth subsections, which have been prepared in direct response to questions asked by the city partners. Whereas the extended introduction section outlines a framework for strategic heat planning and discusses a number of *Key Concepts*, the first in-depth subsection presents a dedicated feasibility study for district heating in the city of Bilbao, while the second in-depth subsection presents answers to questions relating to extensions of current district heating systems and pricing of district heat, raised by the city of Vienna.

Contextually, this report is an output from work package 2 (WP2) in the project, in fact, it is the second out of four WP2 accounts which relate to the work within the local working groups to establish heating and cooling (H/C) outlooks as part of their respective strategic heat plans. For overview and clarity, these four accounts are listed below, with associated deliverable numbers, dissemination levels, and due dates by project month and datum, in parentheses:

- 1. The initial presentation *Input for H/C outlook 2050* (Deliverable 2.1, confidential, M3, September 2020)
- 2. This report, *Draft recommendations for H/C outlook 2050* (Deliverable 2.2, confidential, M12, June 2021)
- 3. *H/C outlook 2050 of cities with cross-city synthesis* (Deliverable report 2.6, public, M26, August 2022)
- 4. *Recommendations for cities' H/C supplies & demands in 2050* (Deliverable report 2.7, public, M27, September 2022).

By this sequence of outputs, it should be clear that the recommendations, the comments, the rhetorical questions, and the critique, put forward in this report is, as indicated by the title, of draft character, that is, of preliminary nature certainly not yet final by no means. On the contrary, what is intended by this output structure is the facilitation of an iterative and communicative process for the continued improvement of the heating and cooling outlooks.

In summary, the introductory section of this reports provides some references regarding approaches whereby to go about energy planning and strategic heat planning in particular. A main reference is made to a three-phase framework introduced through the recent Hotmaps project, but alternative approaches are also mentioned. Three thematical key concepts are also introduced, where the first, *Central and individual solutions*, relates to energy efficiency measures and the important quantity of heat demand density, the second, *Energy quality and temperature levels*, addresses the optimal organisation and operation of energy infrastructures and systems, and the third, *Non-technological dimensions*, discusses economic and political barriers and opportunities. Underneath these three thematical concepts, the following *Key concepts* are also mentioned and elaborated upon in the introductory section:

- *Path Dependency*
- *Technology Lock-in*
- *Energy System Integration*
- *Population Development Trend*
- *Urbanisation Rate*
- *Heat Demand Density (Ground Density)*
- *Local Conditions*
- *Strategic Heat Planning*
- *Structural Energy Efficiency Measures*
- *Individual Energy Efficiency Measures*
- *Industrial Symbiosis*
- *Parallel and Serial Supply Structures*
- *Excess Heat Recovery Rate*
- *Excess Heat Utilisation Rate*
- *Best Available Technology (BAT)*
- *Best Available Organisation (BAO)*
- *Critical Choices*

The draft recommendations presented separately for each of the six cities throughout the report, may in conclusion be summarized topically according to the following main items:

- Where district heating doesn’t exist today, assess its viability in your city by spatial mapping of assets and demand and perform feasibility studies to assess investment and operational costs, potential emission reductions, and resource efficiency improvements possible by its future deployment. Assess in parallel other solutions, such as electrification, and make energy system level comparisons.
- Where district heating exists today, investigate by what means and measures the current system can be extended and more optimally used. Can current connection rates be increased, for example by dedicated densification policies for certain districts in your city, or by the introduction of mandatory connection by zoning. Can innovative

and more appropriate tariff models be used to expand the system's customer base. Further, consider how current operational temperature levels of your system may be lowered in the future. The obtainment of lower system temperatures is important for cost-effective integration of renewables, such as deep geothermal and solar thermal resources, and low-temperature excess heat sources, and therefore represents a key to unlock successful actions to decarbonise current networks. Don't forget waste management. Whichever stand your city may take in view of waste, whether to avoid it, compost it, or reuse it, some of it will be left over and in need of some kind of treatment, and landfilling is, of course, not an option in our day and age.

- In all instances, evaluate and put in effect programs by which the current building stock is retrofitted and refurbished so as to obtain reduced heat demands for space heating and domestic hot water preparation. Irrespective of what system solution are preferred for the heating and cooling supply in your city, end-use demands need to be reduced as far as possible in view of a cost-optimum relative investments in heat supply.
- Maintain a regional perspective and look closely at whatever resources and synergies that might be utilised in your direct local context. Try to maintain a regional level organisation of your strategic heat planning initiative as well, and make sure the coordination of activities remains within the grasp of those in access of such a regional overview. It was an illusory luxury and leisure of the past to let human activities and settlements develop without such overview planning perspectives, a luxury that we no longer can afford ourselves.

By these concentrated accounts, we let the pen rest for now, with just one final recommendation: try to make friends, try to reach the feeling that you are doing this together for a very good cause. Despite whatever other resources you may have at hand, the dedication, effort, and camaraderie of your colleagues is without doubt the most valuable resource of all.

9. 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. EU, *Directive 2012/27/EU on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC*. 2012, European Parliament and the Council: Brussels.
4. EU, *Directive (EU) 2018/844 ot the European Parliament and of the Council of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency*. 2018, European Parliament and the Council: Brussels.
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. HRE. *Heat Roadmap Europe - A low-carbon heating and cooling strategy for Europe. Available at (2018-11-21): (https://heatroadmap.eu/)*. 2018.
10. Connolly, D., et al., *Heat Roadmap Europe 2050 - First pre-study for EU27*. 2012, Euroheat & Power, Brussels. Available at (2018-12-10): (https://www.euroheat.org/publications/reports-and-studies/heat-roadmap-europe-pre-study-1/).
11. Hotmaps, *Hotmaps - The open source mapping and planning tool for heating and cooling*. 2018: Available at (2018-08-31): http://www.hotmaps-project.eu/
12. ReUseHeat, *Recovery of Urban Waste Heat*. 2018: European Union's H2020 Programme under grant agreement 767429. Available (2021-06-21): https://www.reuseheat.eu/.
13. 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/.
14. 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.
15. 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.
16. 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.
17. 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.

18. Kicherer, N., P. Lorenzen, and H. Schäfers, *Design of a District Heating Roadmap for Hamburg.* Smart Energy, 2021: p. 100014.
19. 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.
20. Persson, U. and S. Werner, *District heating in sequential energy supply.* Applied Energy, 2012. **95**: p. 123-131.
21. Persson, U., et al., *Heat Roadmap Europe: Heat distribution costs.* Energy, 2019. **176**: p. 604-622.
22. Energistyrelsen, *Individual Heating Plants and Energy Transport: Technology Data for Energy Plants, May 2012*. 2012: Energistyrelsen (Danish Energy Agency).
23. EU, *Directive 2004/8/EC on the promotion of cogeneration based on a useful heat demand in the internal energy market and amending Directive 92/42/EEC*. 2004, European Parliament and the Council: Brussels.
24. 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).
25. 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.
26. Lund, H., et al., *The status of 4th generation district heating: Research and results.* Energy, 2018. **164**: p. 147-159.
27. Persson, U., B. Möller, and E. Wiechers, *Methodologies and assumptions used in the mapping. Deliverable 2.3: A final report outlining the methodology and assumptions used in the mapping. August 2017*. 2017: Heat Roadmap Europe 2050, A low-carbon heating and cooling strategy. Available at (2018-12-10): (https://heatroadmap.eu/wp-content/uploads/2018/11/D2.3_Revised-version_180928.pdf).
28. 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).
29. Persson, U. and S. Werner, *Heat distribution and the future competitiveness of district heating.* Applied Energy, 2011. **88**: p. 568-576.
30. Frederiksen, S. and S. Werner, *District heating and cooling.* 2013: p. 586.
31. AB, S.F. *Kulvertkostnadskatalog (The district heating pipe cost report)*. 2007. Stockholm.
32. Sánchez-García, L., *Feasibility study of a district heating system in the Spanish city of Gijón*. 2017: Halmstad. p. 114.
33. Werner, S., *Fjärrvärme till småhus – värmeförluster och distributionskostnader (Sparse district heating – heat losses and distributions costs)*. 1997, Svensk Fjärrvärme (The Swedish District Heating Association): Stockholm.
34. 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/).
35. Pezzutto, S., et al., *Heated gross floor area density map of buildings in EU28 + Switzerland, Norway and Iceland for the year 2015*, H. Project, Editor. 2018.
36. Pezzutto, S., et al., *Heat density map (final energy demand for heating and DHW) of buildings in EU28 + Switzerland, Norway and Iceland for the year 2015*, Hotmaps Project, Editor. 2018.
37. Diputación Foral de Vizcaya, *Catastro de Vizcaya*. 2021.
38. Fernandez, J., L. del Portillo, and I. Flores, *A novel residential heating consumption characterisation approach at city level from available public data: Description and case study.* Energy and Buildings, 2020. **221**: p. 110082.
39. Danish Energy Agency. *Technology Data for Energy Plants for Electricity and District heating generation*. 2018. Copenhagen.
40. European Commission, *Eurostat Database.* 2021.
41. Instituto para la Diversificación y Ahorro de la Energía (IDAE). *Analyses of the energy consumption of the household sector in Spain*. 2011. Madrid.

42. Instituto para la diversificación y el ahorro energético (IDAE), *SPAHOUSEC II: Análisis estadístico del consumo de gas natural en las viviendas principales con calefacción individual*. 2019.
43. Werner, S., *The heat load in district heating systems*. 1984, Chalmers tekniska högskola. p. 199.
44. Danish Energy Agency and Energinet, *Technology Data – Renewable fuels*. 2021.
45. Lagoeiro, H., et al. *Heat from Underground Energy London*. in *Proceedings of the CIBSE Technical Symposium, Sheffield, UK*. 2019.
46. Borgholm, H.E. *A new heat recovery and desulphurization plant for 4 wet kilns in Aalborg Portland*. in *[1993] Record of Conference Papers 35th IEEE Cement Industry Technical*. 1993.
47. Menéndez, J., et al., *Feasibility analysis of using mine water from abandoned coal mines in Spain for heating and cooling of buildings.* Renewable Energy, 2020. **146**: p. 1166-1176.
48. TPF-GETINSA-EUROESTUDIOS, *Proyecto de ejecucion de district heating geotérmico con agua de mina a diferentes edificios del entorno del Pozo Barredo en Mieres (Asturias).* 2018.
49. Støchkel, H.K., B.L. Paaske, and K.S. Clausen, *Inspirationskatalog for store varmepumpeprojekter i fjernvarmesystemet*. 2017.
50. Koffi, B., et al., *CoM default emission factors for the Member States of the European Union.* 2017.
51. Turismo, M.d.I.E.y. and M.d. Fomento. *Factores de emisión de CO2 y coeficientes de paso a energía primaria de diferentes fuentes de energía final consumidas en el sector edificios en España*. 2014.
52. Red Eléctrica de España. *Sistema de información del operador del sistema*. 2021 [cited 2021; Available from: https://www.esios.ree.es/es.
53. EMD International A/S. *Skagen District Heating*. energyWEB 2021; Available from: https://www.emd.dk/energy-system-consultancy/online-presentations/energyweb/.
54. Gadd, H. and S. Werner, *Thermal energy storage systems for district heating and cooling*, in *Advances in Thermal Energy Storage Systems: Methods and Applications*. 2015, Elsevier Inc. p. 467-478.
55. Danish Energy Agency, *Technology data for energy storage*. 2020.
56. Arana, I. and J.C. Cardenal, *Ejecución de las obras de Rehabilitación Energética del Edificio y tendido de montantes de red de calor por fachada y su acometida a viviendas del edificio situado en Eulogio Serdán nº 8, del barrio de Coronación en Vitoria-Gasteiz*.
57. Comisión Nacional de los Mercados y la Competencia, *Resolución de 18 de marzo de 2021, de la Comisión Nacional de los Mercados y la Competencia, por la que se establecen los valores de los peajes de acceso a las redes de transporte y distribución de electricidad de aplicación a partir del 1 de junio de 2021*. 2021, Boletín Oficial del Estado.
58. Agency, D.E. and Energinet. *Technology Data for Individual Heating Installations*. 2016. Copenhagen.
59. CYPE Ingenieros S.A., *Generador de precios de la construcción*. 2021.
60. Comisión Nacional de los Mercados y la Competencia (CNMC), *Informe sobre anteproyecto de ley por la que se crea el fondo nacional para la sostenibilidad del sistema eléctrico - Expediente núm.: IPN/CNMC/050/20*. 2021.
61. Spain, *Boletín Oficial del Estado.*
62. (INE), I.N.d.E., *INEbase.* 2017.
63. Magnusson, D., *Between municipal and regional planning: the development of regional district heating systems in Stockholm from 1978 to 2010.* Local Environment, 2011. **16**: p. 319-337.
64. 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.
65. Lygnerud, K., E. Wheatcroft, and H. Wynn, *Contracts, Business Models and Barriers to Investing in Low Temperature District Heating Projects.* 2019. **9**(15): p. 3142.
66. Wheatcroft, E., et al., *Model-Based Contract Design for Low Energy Waste Heat Contracts: The Route to Pricing.* 2021. **14**(12): p. 3614.
67. Dyrelund, A., et al., *Varmeplan Danmark 2010.* 2010.
68. Gåverud, H., K. Sernhed, and A. Sandgren, *Kundernas uppfattning om förändrade prismodeller*. 2016.
69. Öresundskraft. *Öresundskrafts fjärrvärmepriser*. 2021 [cited 2021 21-05-2021]; Available from: https://www.oresundskraft.se/villa/fjarrvarme/fjarrvarme-priser/.
70. Song, J., F. Wallin, and H. Li, *District heating cost fluctuation caused by price model shift.* Applied Energy, 2017. **194**: p. 715-724.

71. Manente, G., et al., *Optimization of the hydraulic performance and integration of a heat storage in the geothermal and waste-to-energy district heating system of Ferrara.* Journal of Cleaner Production, 2019. **230**: p. 869-887.
72. Iren luce gas e servizi. *Prezzi teleriscaldimento - Periodo 2021*. 2021 [cited 2021 21-05-2021]; Available from: https://www.irenlucegas.it/business/condomini/teleriscaldamento.
73. Affaldvarme Aarhus. *Varmeplanaarhus.dk*. 2021 [cited 2021 21-05-2021]; Available from: https://www.varmeplanaarhus.dk/SitePages/Home.aspx.
74. Diget, T., *Motivation Tariff - The key to a low temperature district heating network.*, in *Hot & Cool Magazine*. 2019: Frederiksberg. p. 19-22.
75. Fjernvarme, V. *Incitamentstarif 2021*. 2021 [cited 2021; Available from: https://www.viborgvarme.dk/media/1763/incitamentstarif-graf-og-skema-2021.pdf.
76. Fjernvarme, R. *https://www.roendefjernvarme.dk/%C3%B8konomi/priser/*. 2021 [cited 2021; Available from: https://www.roendefjernvarme.dk/%C3%B8konomi/priser/.
77. Hofor. *Prisen på fjernvarme 2021 for privatkunder*. 2021 [cited 2021; Available from: https://www.hofor.dk/privat/priser-paa-forsyninger-privatkunder/prisen-paa-fjernvarme-2021-for-privatkunder/.
78. Aalborg Forsyning A/S. *Priser på fjernvarme*. 2021 [cited 2021; Available from: https://aalborgforsyning.dk/privat/priser/.
79. 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/.

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