Report on the amounts of urban waste heat accessible in the EU28

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Update note:

By phrases used in this report such as "in the original work", "in the original version", "as from the original assessment", "as stated previously", and similar, is meant the ReUseHeat D1.4 report, revised version, dated 2020-05-31 (Persson, U., H. Averfalk, S. Nielsen and D. C. Moreno (2020). Accessible urban waste heat. Deliverable 1.4 (Revised version): https://www.reuseheat.eu/wp-content/uploads/2021/02/D1.4-Accessible-urban-waste-heat_revised-compressed.pdf

After stiff resistance throughout the last decade, maintaining the perhaps merely academic attitude of preferring "excess heat", rather than "waste heat", as the proper nomenclature to use when labelling secondary residual energy from thermal processes, the authors have here surrendered (at least temporarily) and adheres throughout this report solely to the more popular annotation "waste heat". Whether such an adaption has any significance for the better understanding of the studied topics among our readers, is questionable since the word "waste" is and remains distinctly associated with rubbish (garbage, trash, litter etc.), both with respect to itself (waste generation) and to its management by incineration (Waste-to-Energy), while being only ambiguously associated with rejected heat from energy conversion processes. However, since "waste heat" apparently has won the battle, and furthermore is the terminology most often used in European Union legislation, we recognise the importance of using the term understood and used by the majority, irrespective of its inferior ability to encompass the phenomena at hand.

A similar adaptation would perhaps be conceivable also with respect to the very common European use of the "watt-hour" over the Joule, in terms of energy units. Here we continue to use the Joule, as the recognised *Système international d'unités* dimension by which thermal energy is quantified, although, occasionally, we may also use the "watt-hour" unit for quick transparency and easier reading.

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ReUseHeat website: www.reuseheat.eu

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Executive summary

This report presents the updated and final results from the work performed in Task 1.2 of the ReUseHeat project to assess the accessible EU28 urban waste heat recovery potential from seven unconventional waste heat sources: data centres, metro stations, food production facilities, food retail stores, residential sector buildings, service sector buildings, and waste water treatment plants. The report focusses on recent data and model updates for the EU28 in total (EU27 plus the United Kingdom), as well as for the project demonstration sites, while less focus is directed towards the original methods and approaches developed for these models; all of which have been described in previous accounts.

In terms of data updates, monitoring data from demonstration site operations and public responses to our online project questionnaire on real-world urban waste heat recovery initiatives, are presented and evaluated in overview summary. Regarding model updates, the assessments of urban waste heat potentials from data centres and metro stations have been refreshed by use of new underlying input data, by the configuration of existing and the addition of new model parameters, as well as by reference to later year energy statistics. For the modelling of the total EU28 potential, utilising a dataset for the geographical representation of current urban district heating areas more detailed than the previous one, renders by spatial analytics, under the same "inside or within 2 kilometres of urban district heating areas" default setting as used before, an updated and more accurate assessment of the distances and the vicinity by which low-grade urban waste heat sources are located relative current demand locations.

We maintain in this report also our application of the two concepts "available" waste heat and "accessible" waste heat, which, in combination with spatial constraints, are used to distinguish between resource potentials and utilisation potentials. For the total count of activities elaborated in this update (70,862 unique point-source activities compared to the original 70,771), the total available waste heat potential is assessed at some 1849 petajoule per year (~514 terawatt-hours), compared to the original 1842 petajoule per year. At the default spatial constraint setting, the final available waste heat potential is estimated at ~800 petajoule per year (~222 terawatt-hours) from a thus reduced subset of 22,756 unique point-source locations (960 petajoule per year from 27,703 unique facilities in the original), which here corresponds to a final accessible EU28 waste heat utilisation potential anticipated at 1173 petajoule (~326 terawatt-hours) annually (previous assessment at 1410 petajoule annually).

For improved dissemination and exploitation of project results, a new web map; *the European Waste Heat Map*, has been developed and made available at the ReUseHeat project web page where point source data from this work may be viewed and shared.

1 Introduction

The ReUseHeat project (*Recovery of Urban Excess Heat* [1]), is a European Horizon 2020-project under the call H2020-EE-2017-RIA-IA, in response to topic EE-01-2017; Waste heat recovery from urban facilities and re-use to increase energy efficiency of district or individual heating and cooling systems. The project started in October 2017 and was anticipated to end after 48 months in September 2021 but will instead – due to a twelve-month prolongation agreed in a 2020 project amendment in response partly to effects of the covid-19 pandemic (Amendment Reference No AMD-767429-37, signed 2020-08-05) – reach its end later this year; in September 2022.

The project builds on previous knowledge and data from several other EU funded projects (notably Celsius [2], Stratego [3], Heat Roadmap Europe [4], Hotmaps [5], and sEEnergies [6]), and intends to overcome both technical and non-technical barriers towards the unlocking of urban waste heat recovery investments across Europe. With this outspoken inclusion of and emphasis on non-technical barriers, the project is of particular relevance and interest since the master-key grinding for such an "unlocking" is expected, by a more or less unanimous research community in the field, to fit only if e.g. organisational, legal, and financial, aspects of structural energy efficiency improvements (i.e. large-scale waste heat recoveries by means of distribution in district energy systems) are properly understood and addressed.

Regarding the vanquish of technical barriers, the project aims to demonstrate, at TRL8 (Technology Readiness Level 8) and by developing four real-world case studies, a.k.a. demonstration sites (demo-sites), first of their kind advanced, modular, and replicable, systems enabling the recovery and reuse of low-grade waste heat available at the urban level. By "low-grade waste heat" is meant in this context low-temperature, secondary, residual, "excess" heat from so-called "unconventional sources", that is, from sources and sectors not associated with traditional energy and industry sector waste heat recovery activities ("conventional sources"), which in principle take place at higher temperature levels and by larger capacities and magnitudes.

To fulfil these intentions, the focus in the ReUseHeat project has been directed towards two main areas. On the one hand, the study of non-technical dimensions that may impact on the viability and feasibility of waste heat recoveries in Europe, such as for example political [7], contractual [8], and business model aspects [9]. On the other hand, the realisation of four original demonstration sites (Brunswick (DE), Bucharest (RO), Madrid (ES), and Nice (FR)), where four (out of seven) project-considered unconventional urban waste heat sources (Data centres, Metro stations, Cooling of service sector buildings, and Waste water treatment plants, respectively) were planned to be installed, operated, and monitored during the project lifetime, one at each location.

As a complement and contextual reference to these two main focus areas, additional work has also been performed according to the original work description to model and estimate the overall European Union potential for this type of low-grade urban waste heat, a work mainly performed during the first half of the project lifetime (see e.g. references [10-15]). One of the key outputs from these estimates, the deliverable report D1.4: Accessible urban waste heat [16], which summarized a restrained EU28 (EU27 plus United Kingdom) accessible low-grade waste heat potential at some 1.41 EJ (~392 TWh) considering a final cut of some 27,700 unique facilities inside or within two kilometres of current district heating areas, constitutes the original work (EU potential assessments, source category models, demo-site descriptions etc.) which is the main subject for this update.

This report has been created during the period from February to May 2022 and is the result of a collaboration between Halmstad University in Sweden (Task leader of Task 1.2 (Quantification of accessible urban waste heat) and lead beneficiary for deliverable D1.9) and Aalborg University in Denmark (Work package leader of work package 1 (WP1: Urban waste heat potential identification)). The report is structured in a simple design so as to first introduce the reader to the study background and context, its objectives and basic concepts (main section 1), then to emphasise the two main update dimensions, namely the demos-sites on the one hand (main section 2) and the model updates on the other (main section 0). In the demo-site section, a subheading design, repeated for each of the four demo-site source categories, is arranged to provide coherent accounts of gathered monitoring data and questionnaire responses, as well to present each respective demo-site visually and quantitatively with respect to found waste heat potentials at these locations. For the main section on model updates, which, in terms of source categories, concern data centres and metro stations, and, in terms of infrastructures, concern district heating areas (the spatial representation of current urban areas with district heating), key characteristics and outputs from the performed model updates, including comparisons to previous assessments, are presented together with a brief account of the spatial analysis performed to produce the new modelling output.

The main result of the report, that is the updated estimate of the potential for urban low-grade waste heat accessible in the EU27 plus United Kingdom, is presented in main section 4 with emphasis on available and accessible waste heat[1]. As in the original work, the default setting in terms of spatial constraints used to determine the utilisation potential is the same here as before, i.e., the delineation according to facility locations where only those facilities located inside or within two kilometres of current district heating areas qualify. However, since this update utilises a more detailed and narrower dataset for the spatial representation of current district heating areas compared to the original, this has a considerable influence on the final results. The update results are further summarised in association with some concluding remarks in main section 5. An appendix section is also attached at the end of the report.

1.1 Background and context

At the outset of the ReUseHeat project, the original work description (Grant Agreement 767429, dated 2017-08-22) included only one deliverable output which was to explicitly reflect the work under Task 1.2 in WP1. This deliverable output, the D1.4 report, titled *Accessible urban waste heat,* with descriptive subtitle *Report on the amounts of urban waste heat accessible in the EU28*, was one of six initially planned WP1 deliverable outputs, most of which were intended for completion during the first couple of years of project duration. Already at the proposal-writing stage, the main idea concerning how to approach data acquisition for the work in Task 1.2 had been conceived as primarily to rely upon various EU-wide datasets and models developed in previous and ongoing European projects, such as those mentioned above.

In parallel, work in Task 1.1 (Data collection, creation and maintenance of database) set out early-on to develop a data collection approach [17], among other in the form of a web-based questionnaire created from a set of well-elaborated questions (online survey [18]). The idea was that this questionnaire would be filled-in by various stakeholders as the project progressed and that the information thereby gathered then could be used to gain knowledge on urban waste heat opportunities at determined locations (e.g., site-specific availabilities of waste heat together with information on associated metrics such as flow rates, temperature levels etc.). Despite the fact that the project has had to struggle with a persistent low response rate to this questionnaire (irrespective of several campaigns), the unfortunate design, and perhaps unclear description, of these analogue but separate Task 1.1 and Task 1.2 ideas likely promoted a fallacious comprehension that the EU potential assessments of Task 1.2 was dependent on the questionnaire information gathered in Task 1.1 for its realisation, which was never the intention.

During the second general assembly meeting in Bucharest (March 2018), the different comprehensions of these ideas became apparent during a discussion concerning the linkage – or rather the missing linkage, as it seemingly was apprehended – between data and information used in the EU potential assessments (Task 1.2) and that to be gathered through the online questionnaire (Task 1.1), as well as that to be gathered at the demo-sites, i.e. monitoring data to be assembled and managed in association with Task 4.3 (Monitoring management platform) in work package 4 (WP4: Monitoring and Evaluation of

[1] The concepts of “available” and “accessible” waste heat are used with special connotation and meaning in this work. See subsection 1.3.2 for further references.

demo cases). The resolve in response to this discussion ended in an agreement that the D1.4 deliverable report was to be updated at the end of the project to ensure that empirical information (questionnaire information and demo-site monitoring data) could be included as references for comparison and evaluation. Formally, this resulted in the creation of a new deliverable under WP1, the D1.9 deliverable report (this report), which was part of a 2019 project amendment (Amendment Reference No AMD-767429-25, fully signed on 2019-08-06).

In addition, the initial version of the D1.4 deliverable report (first submission on 2018-11-30) was rejected during the first periodic report review and accepted during the second only after the preparation of a revised version (2020-05-31), in the following referred to as the "original work" [16]. The review of the initial version expressed concerns about the validity of the deliverable, which was found limited due essentially to issues of accuracy and completeness. For the former, the underlying observations referred chiefly to the above-mentioned discussion and queries towards whether, by comparison, the empirical inputs from the Task 1.1 questionnaire and those from the WP4 demo-site monitoring data, could be used as evidence-based, real-world, references to facilitate an evaluation and validation process of the proposed EU potential assessment of Task 1.2. Hereby, the accuracy and reliability of the found EU potentials could be improved, either by their found discrepancies relative to these empirical references, or by their reaffirmation according to the same. For the latter, the initial failure to comply with the intended study scope was corrected by the preparation and inclusion of three additional unconventional heat source categories in the revised version: Rejected heat from refrigeration processes in the food production sector; rejected heat from refrigeration processes in the food retail sector; and rejected heat from the cooling of buildings in the residential sector.

In association with the second periodic report review (review consolidated report dated 2020-11-06), the acceptance of the revised version of the D1.4 report was accompanied with the following stated topics to be addressed in the upcoming D1.9 report:

- Annex 1, Expert opinion on deliverables
    - On D1.9… the updated information about the demo-sites (Metro system of Bucharest and the hospital in Madrid) not updated in the current version of the deliverable has to be provided. As also stated, the work performed post November 2018 to develop and improve the models presented in the original work, have to be included (D1.4).
- Overall assessment, 5. Recommendations concerning future work, if applicable
    - It is recommended that the update of D1.9 will include empirical input from demo-sites, responses from the web-based survey in WP1 and 2020 update of the Data Center Map.
- Objectives and workplan
    - D1.9… will update and address information that in D1.4 is not included, such as Berlin and Madrid demo-sites and the development and improvement of the models.

As further described in the next subsection; 1.2 Objective and scope, the main aim and ambition of this report is therefore to respond to the above-listed review topics and, as well, in line with the report title, to provide a re-calculated and thus updated assessment of the amount of urban waste heat that is accessible in the EU27 member states plus the United Kingdom. In addition, the authors would like to take the opportunity – perhaps becoming here at the late end of the project – to introduce the added value of a novel web-map devoted exclusively to urban waste heat sources! To our current knowledge, no, or only very few, such data repositories are publicly available under an EU-wide scope today[2]. The design and contents of this web-map, *the European Waste Heat Map*, are further detailed in subsection 1.2.2 and Appendix subsection 7.1 below.

[2] This web-map may be seen as a complement to the Pan-European Thermal Atlas (Peta), which recently was updated to version 5.2 within the context of the sEEnergies project (February 2022).

1.2 Objective and scope

With the main aim of updating the revised version of the D1.4 deliverable report, according to the above-listed topics put forward in the second review report, the objective of this work is to re-calculate the urban low-grade waste heat potential, now with reference to empirical monitoring and questionnaire data, by dedicated model updates regarding source categories data centres and metro stations, and finally, by virtue of refined and improved spatial analysis.

In terms of scope, the assessment includes the member states of the EU27, plus the United Kingdom (UK), regularly labelled “EU28” in this context to maintain coherency with the original work, by which the resulting total potentials are presented in aggregation. The analytical scope in terms of geographical resolution, is very detailed. Five of the studied source categories (data centres, metro stations, food production facilities, food retail stores, and waste water treatment plants) are characterised by geographical coordinates and thus represented as point sources. The remaining two source categories (service and residential sector buildings, respectively) are geographically represented by raster grid cells at hectare resolution (100 x 100 metres).

The assessment also includes quantification, and visualisation, of local potentials for the project demo-sites, which, due to reasons further explained below, during the course of the project have come to involve five cities, not four as originally conceived. The five demonstration site cities and their current statuses are:

- Brunswick: data centres, in operation
- Bucharest: metro station, never reached operation phase and later abandoned
- Berlin: metro stations, two attempted locations to replace Bucharest, none of which reached operation phase
- Madrid: service sector buildings (hospital), in operation, however at another hospital than originally planned
- Nice: waste water treatment plant, never reached operation phase with the intended heat source, have instead developed an application using sea water as heat source.

Regarding the potential assessments for the demo-sites, the source category scope is somewhat wider than that applied for the EU28 potential, since, by the work description, also waste heat from industries, power plants, and waste incinerators, so called unconventional sources, are part of the assessment.

1.2.1 Main data sources

The main data sources used in this work, in addition to those used and referenced in the original report, include first of all the questionnaire and demo-site monitoring data, secondly, various datasets used in association with the model updates, and thirdly, the refined and improved district heating areas dataset. The references to these sources are given either in this subsection, in the original work, or elsewhere in this report in line with the presentation of each respective update topic.

In terms of data, model development and improvements post November 2018 include the acquisition and preparation of the 2020 Data Center Map [19], the development and gathering of traffic intensity information for six (out of 37) metro station cities and download of the public sEEnergies D5.1 district heating areas dataset [20]. For the demo-site monitoring data, aggregated per minute-interval heat pump measurement data from three months of part-time operation at the Brunswick data centre have been made available. Similarly, 15 minute-interval booster heat pump measurement data from the hospital in Madrid has been gathered and aggregated also for a three-month period, but here at full-time operation. From one metro station in Berlin, some eight months of hourly platform temperature and air humidity measurements have been incorporated into our used data sources. For Nice, extensive parameter measurements from the unintended heat recovery application with sea water is, unfortunately, of no relevance for this update.

In terms of questionnaire responses, a total of 89 replies with relevance to this update have been gathered, 77 of which mainly refer to Irish data centres (metro stations: two; cooling from service sector buildings: one; waste water treatment plants: eight), all of which are further described in the following. Given this dull circumstance, and the fact that only two out of five demo-sites have relevant operational data to share at this stage, there are practical limitations to the usefulness of this thought empirical evidence by which to compare and reference the potential assessments.

Although the idea of using local, real-world, evidence (in the form of highly detailed demo-site measurements and query responses) to "validate" continental-level potential assessments in itself is conceivable (given access to adequate number and detail of empirical data), the notion is still flawed by a certain lack of understanding. Overview potential assessments within the energy domain, such as in this work and sometimes referred to as "continental mapping", typically utilises top-down approaches in combination with various numerical and statistical operations to produce – in terms of attributed quantitative properties - generic outcomes and does not pretend, or aim, to render exact, "super-accurate", location-specific results. This latter outcome, rather referred to as "local mapping" and typically based on bottom-up approaches, may indeed be characterised by higher level of detail and accuracy, however, often at the cost of lost aggregation possibilities and spatial limitations.

Hereby, it may be concluded that where generic methods, per definition, are associated with less accuracy compared to particular methods, particular methods are associated with less extent and scope compared to generic methods. If attempting to use data generated by particular methods to "validate" the data resulting from generic methods, one should first consider if the particular data is representative of its species, that is, if the particular data is of sufficient quality and includes sufficient number of observations to resemble any kind of population average? As indicated above, and which will become further apparent in the following, this is not really the case here. With the limited monitoring data and questionnaire responses we have at hand, we have sought to establish and use particular averages and compare them to generic averages as far as possible.

1.2.2 The European Waste Heat Map

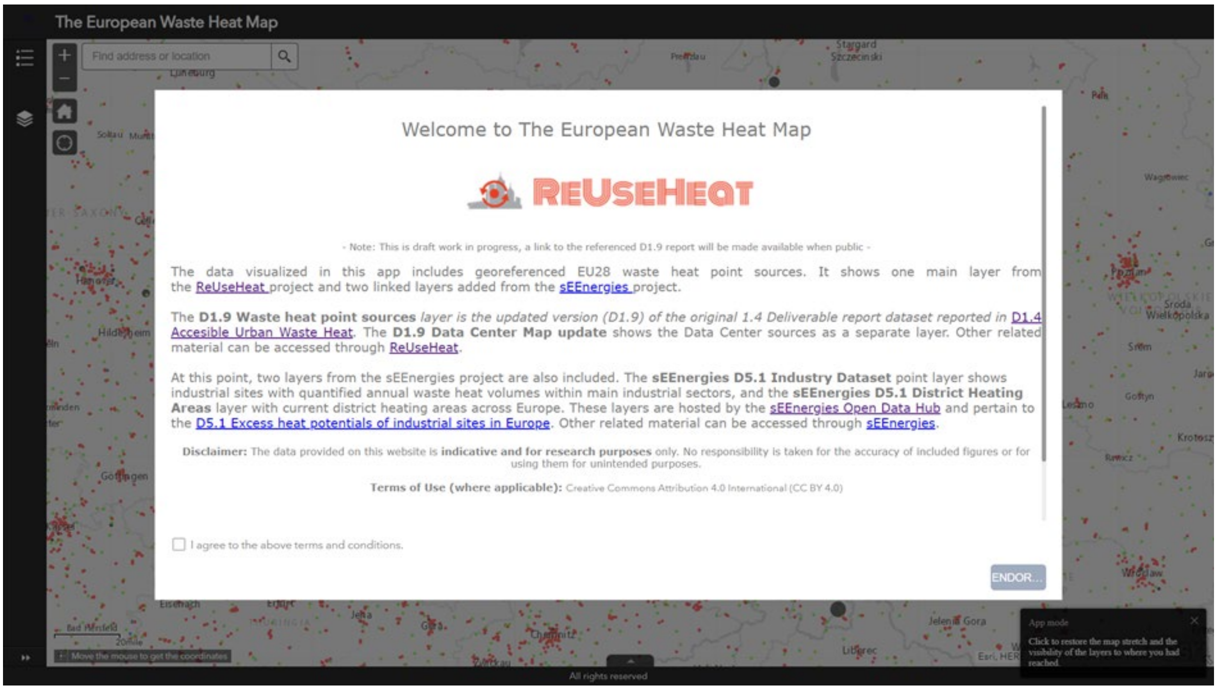

Figure 1. Screenshot of the welcome screen at the new European Waste Heat Map.

The rich and manifold datasets of European urban low-grade waste heat sources created and assembled in this task of the ReUseHeat project constitute the underlying fact-basis upon which the potential estimates are founded. As will become evident for anyone who reads this report to its end, this includes data for more than seventy thousand unique point sources across the elaborated main sources categories, data which, on its own, we believe could be of value for the European community, as its efforts to emancipate itself from fossil fuel dependency now increases in intensity.

Since it was never part of our contractual obligations, we consider it as an extra bonus (something we can and want to do at the end of a long and testing project endeavour) to hereby introduce the novel European Waste Heat Map[3], a public map viewer and repository for waste heat data in Europe which we hope will become a useful asset and tool in support of these efforts [21]. We invite you to visit the new web map by following this link:

https://tinyurl.com/2wvh7ud7

1.3 Basic concepts and approaches

Regarding basic concepts and approaches, we present here principally only those components that are of relevance for the model updates and the refreshed potential assessments in focus. While we therefore refer readers interested to learn more about these ideas and methodologies to their full descriptions in the original work (D1.4), we still take the opportunity in this subsection to reproduce a few of these for orientation and easier reading. In short, this will involve recapitulations of the original methods overview (Table 1), the type processes (subsection 1.3.1), with the schematic overview for the seven source categories (Table 2), the central concepts of available and accessible waste heat (subsection 1.3.2), and the definition of current district heating areas (subsection 1.3.3).

In resumé then, the main methods used in the original work (changes in the update work marked with: *), as summarized in Table 1, may be characterised as semi-heuristic top-down approaches that combine spatial mapping (and modelling) with statistical information and derived quantitative data for each of the respective source categories. The seven unconventional sources modelled share the common feature of having been geographically determined by means of georeferencing in a GIS (Geographical information System), which allows for location-specific quantification of available and accessible waste heat volumes at facility (or ground land area) level, volumes which are then viable for aggregation up to city, national and EU levels.

Table 1. General overview of main methods used in the potential assessments of available and accessible urban waste heat from the seven unconventional sources

Source	Main methods	Quantitative data	Georeferenced data	Comment
Data centres	Statistics-based assessment and spatial mapping	Yes (not on facility level)	Yes	National total volumes (not sufficient data on facility level)
Metro stations	Spatial modelling and mapping	Yes	Yes	Cooling of exhaust air not below 5°C to avoid freezing on evaporator walls (*update: exhaust air not below 10°C)
Food production facilities	Statistics-based assessment and spatial mapping	Yes (not on facility level)	Yes	National total volumes (not sufficient data on facility level)
Food retail stores	Spatial modelling and mapping	Yes	Yes	Modelling of trans-critical CO_2 systems. No use of heat pumps
Service sector buildings	Spatial modelling and mapping	Yes	Yes	Shares of cooled floor areas applied uniformly
Residential sector buildings	Spatial modelling and mapping	Yes	Yes	Extract of hectare cells with plot ratio above 1
Waste water treatment plants	Regression model and spatial mapping	Yes	Yes	Conservative assessment since based on lowest projection towards benchmark level

As can be seen in Table 1, quantitative data at facility level has been retrieved or generated for all source categories expect for that of data centres and food production facilities, why

[3] The European Waste Heat Map is intended as a comprehensive European web map on waste heat sources that could be used to substitute fossil fuels in the heating and cooling sectors and thereby to provide information on alternatives to consider for decarbonisation and green transition. The web map is not limited to datasets developed in the ReUseHeat project but may also include datasets created in other projects and contexts.

alternative approaches have been used for these source categories. Spatial mapping has been used for all categories, in combination with spatial modelling with respect to metro stations, service sector buildings, and residential sector buildings, and by use of a linear regression model with respect to waste water treatment plants. In the comment column, a general note on overall modelling features for each source category is given in brief. For more detailed accounts, see each respective source category section in the original work as well as below for the model updates.

1.3.1 Type processes

The classification and characterisation of unconventional urban waste heat recovery type processes (typical processes and technologies), as established in the original work, are reproduced in the schematic overview for the seven source categories presented in Table 2. By the label "unconventional", a common feature for all of these sources, is indicated firstly that they may all be characterised as low-temperature sources. By "low-temperature sources" in turn, is understood waste heat sources that discharge available waste heat at temperatures well below 50°C (in most instances rather in the interval of 5°C - 40°C), as also outlined in Table 2.

Table 2. Classification and characterisation of typical processes, temperatures, temporality properties, and technologies that represent the seven modelled unconventional waste heat sources

Source	Recovery type	Temperature range	Temporality (diurnal)	Temporality (seasonal)	Heat pump conversion type
Data centres	Server room air cooling systems	25°C - 35°C	Principally constant	Principally constant	Air-to-Water
Metro stations	Platform ventilation exhaust air	*10°C - 35°C	Variable	Variable	Air-to-Water
Food production facilities	Rejected heat from refrigeration processes	20°C - 40°C	Principally constant	Principally constant	Liquid-to-Water
Food retail stores	Rejected heat from refrigeration processes	40°C - 70°C	Principally constant	Principally constant	-
Service sector buildings	Central cooling devices	30°C - 40°C	Variable	Variable	Liquid-to-Water
Residential sector buildings	Central cooling devices	30°C - 40°C	Variable	Variable	Liquid-to-Water
Waste water treatment plants	Post-treatment sewage water	8°C - 15°C	Principally constant	Principally constant	Water-to-Water

Due to this key feature of the studied heat sources, any practical utilisation of this waste heat in current district heating systems (3rd generation district heating systems), which typically operate at supply temperatures in the range from 70°C to 90°C, or higher, requires a temperature lift. In this work, all such utilisation of recovered waste heat, with the exception of rejected heat from refrigeration processes in the food retail sector[4], is perceived to take place by means of (large-scale) compressor heat pumps.

As can be seen further in Table 2, the temperature range given for data centres refers to electrical server room air cooling systems, not to water-circuit cooling systems (which are associated with slightly higher temperature ranges in the order 40°C to 60°C). For metro stations, the stated temperature range refers to the full annual temperature interval present over the year in platform air ventilation shafts (with a model update at 10°C (marked with an: *) representing a fixed model minimum set-point for exit air temperatures partly to avoid ice build-up on evaporator surfaces, and partly to maintain an additional 5°C temperature difference between minimum exit air temperatures and evaporator surfaces, see further subsection 3.2.2 for this model update)).

Rejected heat from refrigeration processes in food production is anticipated in the interval 20°C to 40°C, while in the food retail sector, modelled trans-critical CO_2-systems reject heat at higher temperatures (therefore directly recoverable in district heating systems).

[4] The reason for this is that, for this sector, refrigeration has been modelled as taking place solely with trans-critical CO2-systems, which reject heat at sufficiently high temperatures for direct recovery in district heating systems.

The temperature of heat rejected from residential as well as service sector central cooling devices is anticipated to be found in the interval of 30°C to 40°C, however this is operational specific. For waste water treatment plants, post-treatment sewage water is expected, on average, not to fall below 8°C year-round (12°C as an approximate average).

In terms of temporality, four sources exhibit principally constant features, both on a daily and annual basis. The diurnal load in data centres is principally constant, although by two different load characteristics (user traffic during daytime, server back-up activities during night-time), and operations are normally continuous over the year. Sewage water is generated all year round and treatment processes operate continuously, however, post-treatment flows may occasionally (and locally) be warmer during summer season due to higher ambient temperatures.

The corresponding temporality profiles of metro stations, residential sector buildings, and service sector buildings, are quite different since they all are subject to diurnal as well as seasonal variations. For metro stations, passenger traffic is normally not operational during night-time, and, since ambient air temperatures indirectly influence the temperatures of ventilation exhaust air, seasonal variation is also a factor impacting on the magnitude of waste heat recoverable from this source. For service sector buildings, essentially so with respect to offices, hospitals, schools etc., that is activities which in terms of intensity follow normal working-week patterns, both a diurnal and a seven-day temporality factor is in play. Perhaps less so, but still present, is also a sensitivity to seasonal variations due to changes in ambient temperatures.

Table 2 further distinguishes the heat pump conversion type (or operational configuration), meaning by which physical form, through which rejected heat from the considered sources are recovered. As can be seen, heat recovery from the first two source categories, data centres and metro stations, is conceived as taking place by means of air-to-water heat pump configurations. In retrospect, and in view of sector developments post 2020, applying instead water-to-water heat pump configurations as alternative operational configurations in both these instances would perhaps have been more appropriate. For the remaining source categories, liquid-to-water configurations are conceived for residential and service sector buildings, while a water-to-water heat pump conversion type is applied for waste water treatment plants.

1.3.2 Available and accessible waste heat

As heat recoveries from the studied unconventional urban waste heat sources are modelled to take place by means of heat pumps[5], the following principles for heat pump operations are used uniformly throughout this work. The foundational outset for this modelling is the basic energy balance for a refrigeration cycle [22], equivalent to that of a heat pump, which may be expresses as:

$$Q_H = Q_L + \mathrm{W} \qquad [\mathrm{J}] \qquad (1)$$

Where, in a heat pump, the heat transferable from the condenser (high temperature side), Q_H (J), is the sum of the heat transferred to the evaporator (low temperature side), Q_L (J), and the amount of work introduced to the process (electricity for a compressor driven heat pump), W (J). From this, the practical COP (Coefficient of Performance) of a heat pump may be written as:

$$COP_{HP,p} = \frac{Q_H}{W} \qquad [\text{-}] \qquad (2)$$

Equation (2) states that the practical COP is the ratio of the usable heat output from the heat pump and the electric energy used in the process. By re-writing Equation (2) with reference to Equation (1), this relation can also be expressed as:

[5] With respect to heat pump operations, which in vapour-compression cycles all rely on refrigerants for their proper function, no attention has been given here regarding what type of refrigerant that may be used in the suggested conversions, nor so to current legislation or commercial aspects that might influence the viability to use certain compounds. In real-world waste heat recovery projects such aspects should of course be addressed.

$$COP_{HP,p} = \frac{Q_H}{Q_H - Q_L} = \frac{1}{1 - \left(\frac{Q_L}{Q_H}\right)} \qquad [-] \qquad (3)$$

If related instead to temperatures, that is if considering the theoretically highest possible COP to be attainable in a heat pump process (corresponding to a reversible Carnot process), the corresponding relationships from Equations (1) to (3) may synonymously be expressed as:

$$COP_{HP,t} = \frac{T_H}{T_H - T_L} = \frac{1}{1 - \left(\frac{T_L}{T_H}\right)} \qquad [-] \qquad (4)$$

In Equation (4), T_H (K), denotes the temperature level at which heat transfer from the condenser occurs, and T_L (K) is the temperature level at which heat transfer to the evaporator takes place. From this it is viable to establish what sometimes is referred to as the Carnot efficiency, η_C [-]; the ratio of practical and theoretical performance which provides an indication of the actual inefficiencies that are associated with real-world heat pump operations:

$$\eta_C = \frac{COP_{HP,p}}{COP_{HP,t}} \qquad [-] \qquad (5)$$

In the modelling of the original work, the practical COP was used also as a sensitivity analysis parameter by evaluating, for all source categories, the impact on the results at three different values: 2.5, 3.0 (default), and 3.5. While the results presented in the main of the original report were those associated with the 3.0 default (with the other two COP values presented in appendix), here we are presenting the results by the COP default only.

According to the above, the heat *available* for recovery from a given waste heat source is here comprehended principally to correspond to that heat which is transferrable to the heat pump evaporator (Q_L). By solving Equation (3) for the quantity Q_H, i.e., the heat possible to transfer from the heat pump condenser at a given practical COP, an expression is found for the useful output of *accessible* waste heat from the conversion[6]:

$$Q_H = Q_L + \left(\frac{Q_L}{(COP_{HP,p} - 1)}\right) \qquad [J] \qquad (6)$$

Hereby, in our withheld nomenclature, *available waste heat* refers to heat available at a source and which is recoverable at the evaporator side of any given compressor heat pump, thus corresponding to Q_L. The significance of this concept is that the assessed potentials for available waste heat is independent of any specific utilisation technology, meaning that these estimations simply state what magnitudes of recoverable waste heat that supposedly is out there irrespective of whatever means by which it might be recovered and utilised. This may be of importance and relevance if evaluating possibilities for waste heat recovery technologies other than those anticipated here.

Accessible waste heat, thus corresponding to Q_H, is understood as that heat which is accessible at the secondary side of any given compressor heat pump; heat rejected from the condenser as the sum of available waste heat plus electric energy (W) introduced to the process. By distinguishing between available and accessible waste heat, a vocabulary is thought to have been given which recognises that the presence of an asset is something quite different from the marketing of a product.

1.3.3 Definition of current district heating areas

Since, when considering how the actual utilisation of low-grade waste heat, recovered as described above in large-scale heat pump configurations, is going to take place in the real world, one soon realises that no such utilisation is conceivable unless some cooling source

[6] Here it might be noteworthy to realise that, at a constant level of available waste heat, the useful output of accessible waste heat will decrease with increasing COP values, since increased COP values indicate that less electric energy is required to drive the heat pump process.

is in contact with these heat pump condensers to receive the accessible heat by means of heat transfer. Throughout this whole work, the cooling source considered consists of existing district heating supply pipes in current European district heating systems. For this reason, a key research question already at the project outset asked what, and by what metrics, information on current European district heating systems is available?

In short, coherent compilations with location-specific data on existing European district heating systems, is, and always has been, a rare commodity typically not available within ordinary statistical repositories. This is in fact the main reason why researchers at Halmstad University (HU) in Sweden started building a European district heating and cooling database already in 2010. Up until its fifth version [23], the geospatial information on recorded district heating cities only included geographical point source coordinates (latitude and longitude), which did not permit area representation. To amend this shortcoming, a first polygon-based representation was obtained in association with the original work [24] by combining the HU database information with that of the Urban Morphological Zones (UMZ) from the European Environment Agency (EEA) [25-27], annotated "UMZDH" areas and exemplified for three European cities in Figure 2.

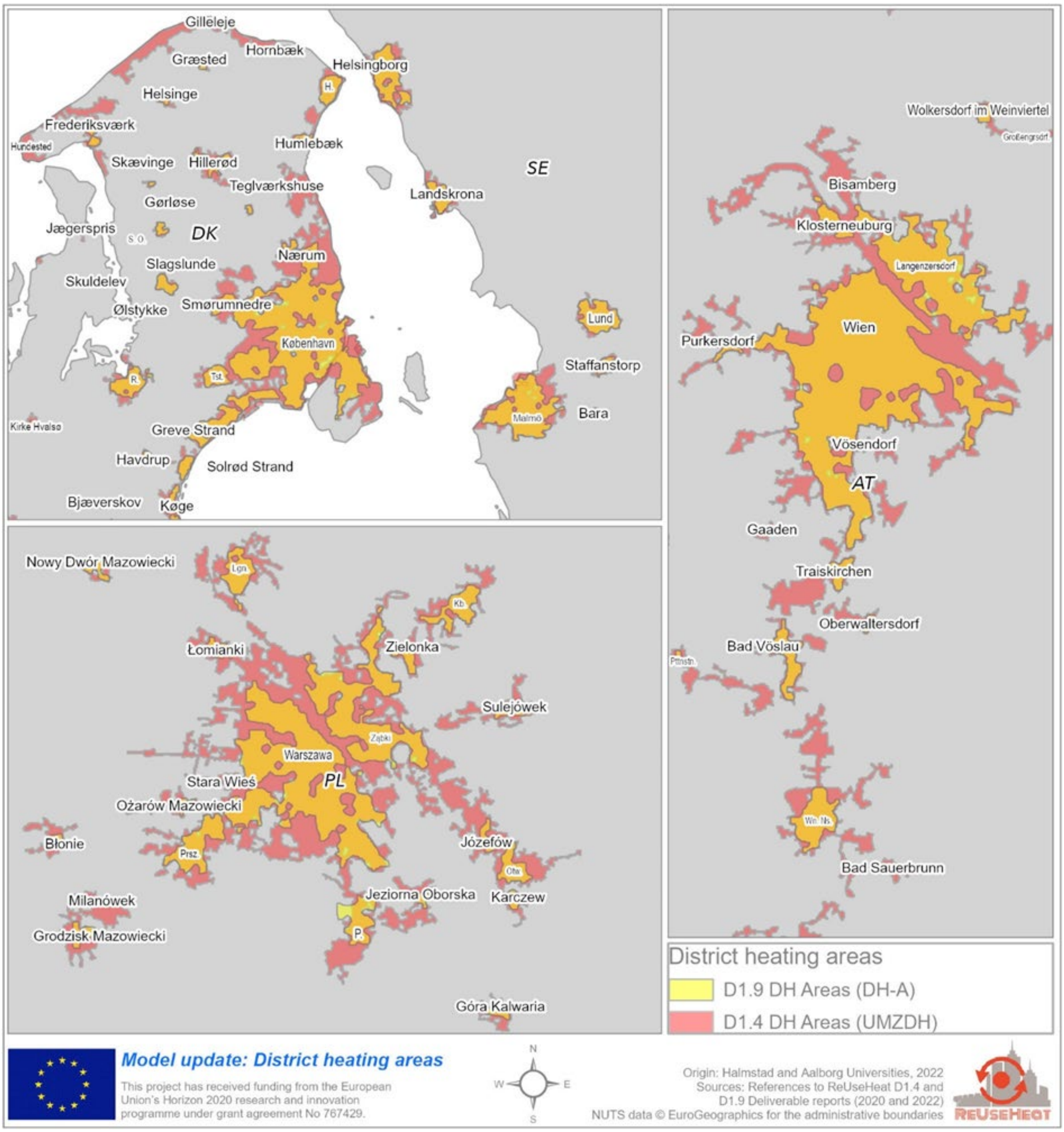

Figure 2. Geospatial representations of current district heating areas by the original (UMZDH) and the update (DH-A) definitions, exemplified for the greater Copenhagen area (top-left), Warsaw metropolitan area (bottom-left), and Vienna with surroundings (right).

Even though the UMZDH areas dataset was an improvement which allowed, for the first time, a geographical delineation with reference to current urban district heating areas, admittedly, these polygons were not very precise as for their sought purpose. While the UMZ areas themselves were based on four[7] (out of 44) selected land use classes interpreted as "urban fabric" in the high-resolution satellite-imagery-based Corine Land Cover database [25, 28], they were in fact only implicitly and vaguely associated to district heating areas. In the original work, this condition was recognised as "true shortcomings in the used data that should be kept in mind when evaluating the study results, and, for the future, as more detailed data on the physical outstretch of European district heating systems may become available, the study approach may be used anew to generate results at perhaps higher accuracy levels" (page 28 in [16]). In this particular sense, it is extra satisfactory to have been given the opportunity to perform this update.

Because for this update, a second polygon-based representation has in fact become available, and this new dataset, the above-mentioned sEEnergies[8]-generated "DH Areas" dataset [20], was developed exactly with these original shortcomings in mind; to increase the accuracy by which current district heating areas may be geographically represented.

The sEEnergies approach involved, as the original did, a spatial matching to the point source records kept in the HU database (by that time in a slightly updated version [29]), but adopted a completely different approach to characterise and outline the corresponding district heating areas. This approach has been documented more fully in [30, 31], but utilises, in short, hectare-level heat demand density data together with a heat demand density classification, a methodology initially developed and established in the Heat Roadmap Europe project [24, 32]. After some post-processing (boundary cleaning, aggregation etc.), the resulting and publicly available polygon layer is that which may also be seen in Figure 2 (here annotated as "DH-A").

The use of heat demand density classification allows for a selection of grid cells with heat demand densities above certain thresholds. For this study, the selection made in the mentioned sEEnergies context, which is thought to represent areas where district heat distribution is likely to have been feasible during the last decades (referring to building heat demands in residential and service sectors at or above 500 GJ/ha), is used unaltered.

Table 3. Number and total land areas of original (UMZDH) and update (DH-A) representations of current district heating areas

MS	UMZDH [n]	DH-A [n]	Difference [n]	UMZDH [km^2]	DH-A [km^2]	Difference [km^2]
AT	327	240	-27%	1955	768	-61%
BE	23	27	17%	4120	543	-87%
BG	21	18	-14%	539	247	-54%
CZ	370	348	-6%	2079	930	-55%
DE	195	215	10%	8962	5361	-40%
DK	407	242	-41%	2002	790	-61%
EE	133	54	-59%	503	143	-72%
EL	3	4	33%	-	13	-
ES	14	14	0%	1189	471	-60%
FI	149	130	-13%	2641	917	-65%
FR	230	224	-3%	8839	4742	-46%
HR	18	17	-6%	445	203	-54%
HU	93	100	8%	1661	596	-64%
IE	2	2	0%	402	227	-43%
IT	62	54	-13%	2526	1372	-46%
LT	35	34	-3%	600	161	-73%
LU	1	1	0%	59	39	-33%
LV	35	31	-11%	473	128	-73%
NL	16	16	0%	1334	780	-42%
PL	379	408	8%	5722	2162	-62%
PT	1	1	0%	342	104	-70%
RO	70	62	-11%	1568	539	-66%
SE	339	226	-33%	3282	1052	-68%
SI	54	39	-28%	263	106	-60%
SK	210	160	-24%	990	399	-60%
UK	93	96	3%	7746	5449	-30%
EU28	**3280**	**2763**	**-16%**	**60242**	**28241**	**-53%**

[7] Corine land use classes that constitute the UMZ layer are: 111 (Continuous urban fabric), 112 (Discontinuous urban fabric), 121 (Industrial or commercial units), and 141 (Green urban areas).

[8] sEEnergies is the short name for the EU Horizon 2020 project *Quantification of Synergies between Energy Efficiency First Principle and Renewable Energy Systems* (No. 846463).

Table 3 presents total numbers and total land areas encompassed by the two datasets, with differences between the new (DH-A) and the old (UMZDH) representations indicated. Interestingly, it can be seen that for the EU28 on average, while the total count of district heating areas is reduced by 16% when moving from the old (3280) to the new (2763) dataset, the total land area of the new dataset amount to less than half of the old. At a total of some 28 thousand square kilometres (which constitute approximately 0.6% of the total EU28 land area, often stated at ~4.4 million square kilometres), the DH-A dataset covers significantly less land area than the UMZDH dataset (at some 60 thousand square kilometres, or some 1.4% of the total EU28 land area). Noteworthy, although some variations occur among the member states, especially regarding number, the EU28-level observations are in most instances representative also of the national level tendencies.

2 Demonstration sites

In this section, the project demonstration sites (demo-sites) are presented orderly in separate subsections according to the corresponding source categories developed at each of them. In each of these subsections, a brief account is given concerning the original demo-site setup configurations, with comments on current status and changes, together with presentations of monitoring data and questionnaire responses gathered for each respective site and source category. The section ends with a presentation of the updated results as for the local urban waste heat potentials at each of the five considered demo-sites.

As an introduction, in summary and as outlined in Table 4, the five demo-sites together host a total of 1866 point source urban waste heat activities (also including 30 conventional sources such as power plants, energy intensive industrial facilities, and Waste-to-Energy plants). Noteworthy, when comparing these numbers with those in the previous assessment, it should be kept in mind that the source categories of food production, food retail, and cooling from buildings in the residential sector, never were part of the original demo-site estimate.

Table 4. Summary overview of the number of waste heat sources located inside or within 20 kilometres of the five demo-sites (all being urban district hearting areas)

Demo Name	Data Centres [n]	Metro Stations [n]	Food Production [n]	Food Retail [n]	Residential Sector Buildings (Inside)	Service Sector Buildings (Inside)	Waste water treatment plants [n]	Conventional [n]	Total Sources [n]
Berlin	19	144	4	645	Yes	Yes	17	13	842
Brunswick	-	-	2	140	Yes	Yes	27	4	173
Bucharest	25	45	3	129	Yes	Yes	10	4	216
Madrid	20	233	7	240	Yes	Yes	36	5	541
Nice	7	-	-	58	Yes	Yes	25	4	94
Total	71	422	16	1212	-	-	115	30	1866

As can be seen in Table 4, most activities are found within the source categories of food retail (65%), metro stations (23%), and urban waste water treatment plants (6%). Data centres, conventional sources, and food production facilities constitute smaller fractions at ~4%, ~2%, and ~1%, respectively. Noteworthy, not all considered source categories are present in all demo-sites. Neither Brunswick, nor Nice, have metro systems in operation, for example, and for Brunswick, the demo-site data centre to be developed appears to be the first of its kind in the city.

2.1 Data centres (Brunswick)

The source category developed in the demonstration site in Brunswick, Germany, is a data centre. As further detailed in the next subsection on monitoring data (and also further below in the model update section 3.1), the heat recovery from this data centres takes place in the form of a two-step configuration where excess heat from a server rack air-cooling system is recovered first in an air-to-water heat exchanger and then from there in a water-to-water heat pump. This configuration is in part an advancement compared to that elaborated in the potential modelling, which anticipates single-step heat recoveries by means of air-to-water heat pumps.

The recovery of data centre waste heat exploits residual energy generated in cooling processes of equipment installed in the server halls, where a cooling demand requires the removal of heat to maintain desired operational temperatures of installed components. Heat is generated in several of the components that constitute the servers, especially so in the processors, the memory chips, and the disk drives. Two main cooling technologies are applicable for use in contemporary data centres today: air cooling or liquid cooling systems. Among currently operating data centres in Europe, a majority appears to be equipped with air cooling systems, so called CRAC (computer room air conditioners) or CRAH (computer room air handlers), which are associated with heat recovery temperatures in the average range of 25°C – 35°C. For liquid cooling systems, since these systems cool the equipment directly within water-circuit embedded servers, the waste heat recovery temperatures are higher, typically in the range of 50°C – 60°C.

Regarding the share of electricity used in a data centre that can be attributed to running its equipment, scientific literature suggests that equipment electricity use in a regular air-cooled data centre correlates strongly with its electricity used for cooling processes, and that between them, a rounded factor two by one constitute the average relation [33], which expressed differently translates into a 2/3 equipment electricity share out of total electricity use (~65%). While others have suggested that more or less all power consumed in a data centre (97%) could be captured in the form of waste heat [34], we have chosen here to maintain a conservative attitude by using 65% as the model default value (65% of total data centre electricity use is conceived as designated for equipment operation and 35% for cooling processes).

As for the local waste heat potential in Brunswick, Figure 3 presents a demo-site overview.

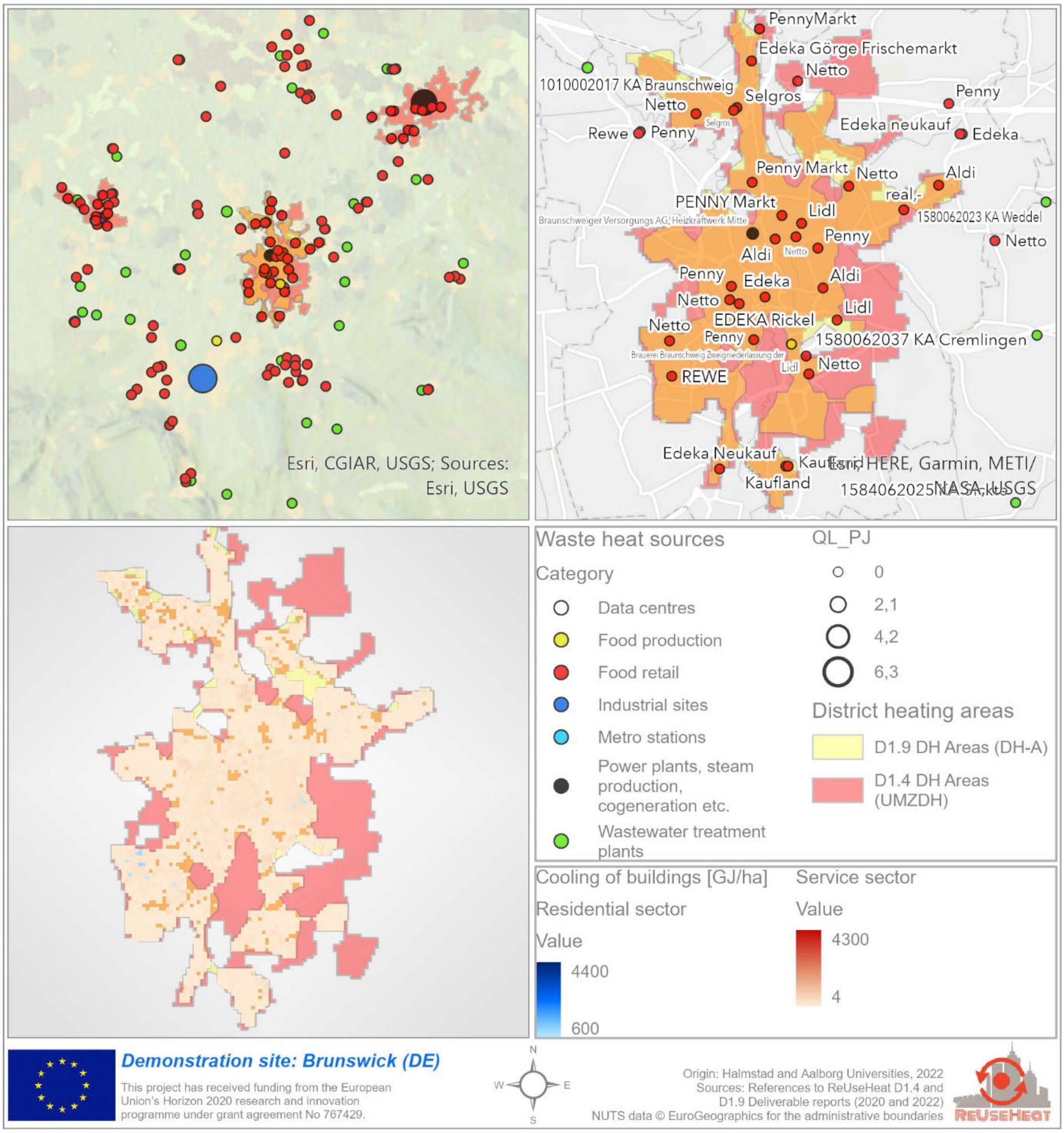

Figure 3. Available waste heat from unconventional and conventional sources in the demo-site of Brunswick (DE), with 20-kilometre overview of point sources (top-left), city close-up with annotated point-sources (top-right), city close-up with rasterised sources (cooling of buildings in residential and service sectors) (bottom-left), and legends (bottom-right). The spatial extent of current district heating areas elaborated in the original work (D1.4) and in this update (D1.9) are both included for reference. Note that for the quantified point source legend, "0" indicates in the case of data centres "No data", otherwise values from close to zero and upwards to the next legend class.

2.1.1 Monitoring data

At the data centre demo-site in Brunswick, a low-temperature district heating network constitutes the cooling source by which the recovered waste heat is utilised. For this heat exchange, the excess heat from the data centre needs to be raised from a temperature of around 25°C to 70°C, and, as mentioned above, this is managed by a two-step configuration consisting of a water-to-air heat exchanger and a water-to-water heat pump. Monitored demo-site data has been retrieved in the period 4th January 2022 to 1st April 2022. It should be noted that the data centre has not been operating at maximum capacity in this period, which could influence the performance and results.

An overview of the monitoring data for the demo-site is shown in Table 5. In terms of temperature level, the supply temperature from the data centre to the heat pump is between 7°C to 29°C, with an average of around 24°C, and seems relatively stable during the four months monitoring period. The supply temperature from the heat pump to the district heating network is between 18°C and 77°C with an average around 70°C from February to April. The COP values are estimated as the relation between the electricity input and the heat output of the heat pump and was highest in January at 6.5 while it was lowest in March at 6.0.

Table 5. Monitoring data from four months of part-load operation at the Brunswick demo-site data centre

Data centre to heat pump					
	Jan	Feb	Mar	Apr	Average
GJ	59.0	230.0	280.8	5.8	143.9
MWh	16.4	63.9	78.0	1.6	40.0
Return					
Return Max ºC	28	26	25	19	25
Return Average ºC	22	19	18	18	19
Return Min ºC	7	10	17	17	13
Supply					
Supply Max ºC	29	26	26	25	27
Supply Average ºC	24	24	24	24	24
Supply Min ºC	7	12	21	23	16
Heat from heat pump					
	Jan	Feb	Mar	Apr	
GJ	79.2	310.0	393.8	7.9	197.7
MWh	22.0	86.1	109.4	2.2	54.9
Return					
Return Max ºC	65	59	50	46	55
Return Average ºC	32	42	45	43	41
Return Min ºC	25	27	41	41	34
Supply					
Supply Max ºC	77	73	73	73	74
Supply Average ºC	37	66	72	72	62
Supply Min ºC	18	25	43	71	39
Electricity use heat pump					
	Jan	Feb	Mar	Apr	
GJ	12.2	50.4	65.5	1.4	32.4
MWh	3.4	14.0	18.2	0.4	9.0
Average COP	6.5	6.1	6.0	6.1	6.2

2.1.2 Questionnaire responses

Data on 77 data centres has been gathered from the ReUseHeat questionnaire. The data relevant to the D1.9 update is presented in Table 6. The temperature level for most data centres is in the range 20 – 40°C, while one is below 20°C and another is in the 60 – 80°C range. In terms of annual volumes of available waste heat, the largest heat recovery potential is in the order of 1.8 petajoule per year (500 GWh/year), while the smallest are around 3.6 terajoule per year (1000 MWh/year). Notably, the average annual volume, determined by reference to the 67 instances for which absolute numbers were given (other than value ranges), was found at 161 terajoule per year (~44.7 GWh per year).

Table 6. Data reports from 77 data centres gathered by means of the ReUseHeat online questionnaire, by fluid type of cooling system, temperature of cooling media, and annually available waste heat volumes

Nr	Fluid type	Temperature [ºC]	Energy volume [TJ/year]	Energy volume [MWh/year]
1	Water	20 - 40	36 - 360	10000 – 100000
2	Water/Glycol mix	< 20	3.6 - 360	1000 – 100000

3	Water	20 - 40	1.8 - 3.6	500 – 1000
4		20 - 40	267	74,067
5	Water	20 - 40	< 36	< 10000
6		20 - 40	3.6 - 360	1000 – 100000
7	Air	20 - 40	3.6 - 360	1000 – 100000
8	NH3 (R717)	60 - 80	3.6 - 360	1000 – 100000
9	Water	20 - 40	3.6 - 360	1000 – 100000
10		20 - 40	80	22,204
11		20 - 40	201	55,845
12		20 - 40	290	80,680
13		20 - 40	50	13,960
14		20 - 40	20	5,584
15		20 - 40	100	27,911
16		20 - 40	27	7,458
17		20 - 40	35	9,768
18		20 - 40	211	58,637
19		20 - 40	211	58,637
20		20 - 40	211	58,637
21		20 - 40	211	58,637
22		20 - 40	25	6,943
23		20 - 40	101	27,922
24		20 - 40	101	27,934
25		20 - 40	34	9,489
26		20 - 40	274	76,016
27		20 - 40	115	31,818
28		20 - 40	5	1,396
29		20 - 40	105	29,257
30	Other	20 - 40	149	41,374
31		20 - 40	227	63,174
32		20 - 40	5	1,396
33		20 - 40	106	29,546
34		20 - 40	136	37,675
35		20 - 40	221	61,511
36		20 - 40	225	62,375
37		20 - 40	5	1,396
38		20 - 40	76	21,056
39		20 - 40	228	63,195
40		20 - 40	274	76,016
41		20 - 40	274	76,016
42		20 - 40	274	76,016
43		20 - 40	110	30,531
44		20 - 40	151	41,883
45		20 - 40	174	48,270
46		20 - 40	151	41,883
47		20 - 40	151	41,883
48		20 - 40	40	11,205
49		20 - 40	151	41,883
50		20 - 40	165	45,807
51		20 - 40	5	1,396
52		20 - 40	288	79,895
53		20 - 40	250	69,372
54		20 - 40	90	25,130
55		20 - 40	90	25,130
56		20 - 40	161	44,676
57		20 - 40	292	80,992
58		20 - 40	481	133,556
59		20 - 40	101	28,122
60		20 - 40	5	1,396
61		20 - 40	60	16,658
62		20 - 40	145	40,340
63		20 - 40	160	44,329
64		20 - 40	219	60,779
65		20 - 40	79	21,836
66		20 - 40	133	36,941
67		20 - 40	387	107,532
68		20 - 40	452	125,651
69		20 - 40	452	125,651
70		20 - 40	10	2,792
71		20 - 40	201	55,900
72		20 - 40	160	44,329
73		20 - 40	372	103,436
74		20 - 40	101	27,922
75	Exhaust gases			
76	Water	20 - 40	114	31,536
77	Water	20 - 40	360 - 1800	100000 – 500000
		Average	161	44660

2.2 Metro stations (Bucharest and Berlin)

Since, as for data centres above, also this source category is subject for a model update in this work, all model related topics for metro stations are presented in subsection 3.2.2 below, while focus here is directed towards the (two) demo-sites, the monitoring data, and the questionnaire responses associated with them.

Put very short, the originally planned metro station demonstration site, Bucharest, Romania, was, for reasons not further commented here, abandoned quite early-on during the project progression and thus never realised in the project. However, as a still active demo-site at the time, Bucharest, and its 20-kilometre surroundings, were indeed part of the local potential assessment in the original work. For this reason, and as well in response to the review request put forward for this update (as outlined in subsection 1.1 above), the updated urban waste heat potentials have been modelled and projected also for the Bucharest case, as presented graphically in Figure 4.

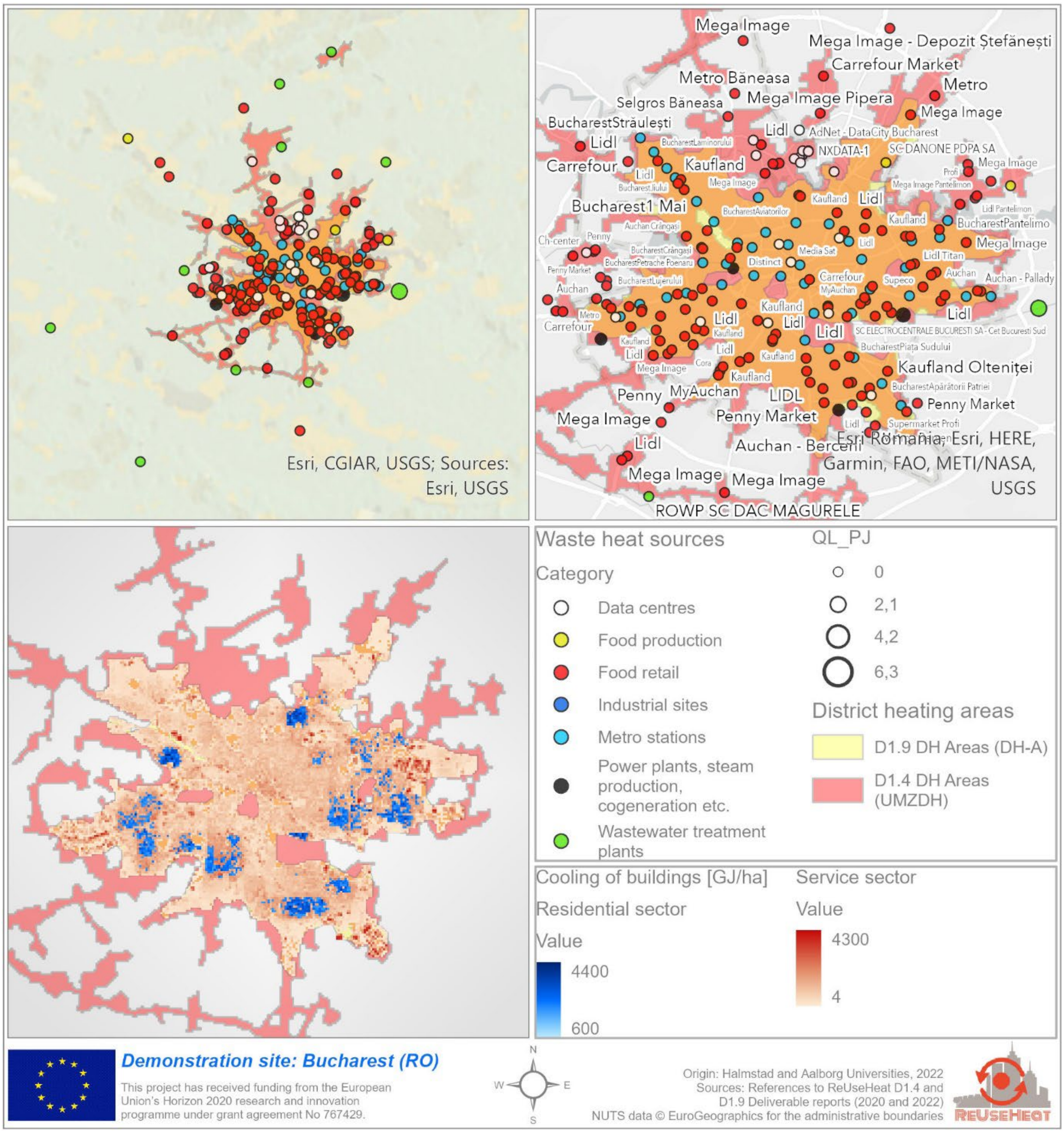

Figure 4. Available waste heat from unconventional and conventional sources in the demo-site of Bucharest (RO), with 20-kilometre overview of point sources (top-left), city close-up with annotated point-sources (top-right), city close-up with rasterised sources (cooling of buildings in residential and service sectors) (bottom-left), and legends (bottom-right). The spatial extent of current district heating areas elaborated in the original work (D1.4) and in this update (D1.9) are both included for reference. Note that for the quantified point source legend, "0" indicates in the case of data centres "No data", otherwise values from close to zero and upwards to the next legend class.

To replace the lost opportunities in Bucharest, several attempts were made to find a new demo-site where heat recovery from this source category could be developed. Eventually, two metro stations in Berlin, Germany, came under consideration, why also Berlin's local urban waste heat potential is mapped here (Figure 5). The first of these, a station close to the technical university, was never realised due to technical reasons, whereafter a second, the Ernst Reuter Platz metro station, came into focus. At this second station, measurement equipment was installed which was to monitor platform temperature and air humidity data, but the heat recovery installation itself could never be realised. The reasons why also this third metro station alternative never reached operational status is beyond the knowledge of the authors, and also beyond the scope of this report.

However, before this second demo-site in Berlin was finally closed down, monitoring data was indeed retrieved from the tunnel in conjunction with the Ernst Reuter Platz station, monitoring data, which is reproduced here, and which includes temperature and relative humidity measurements from June 2021 to February 2022.

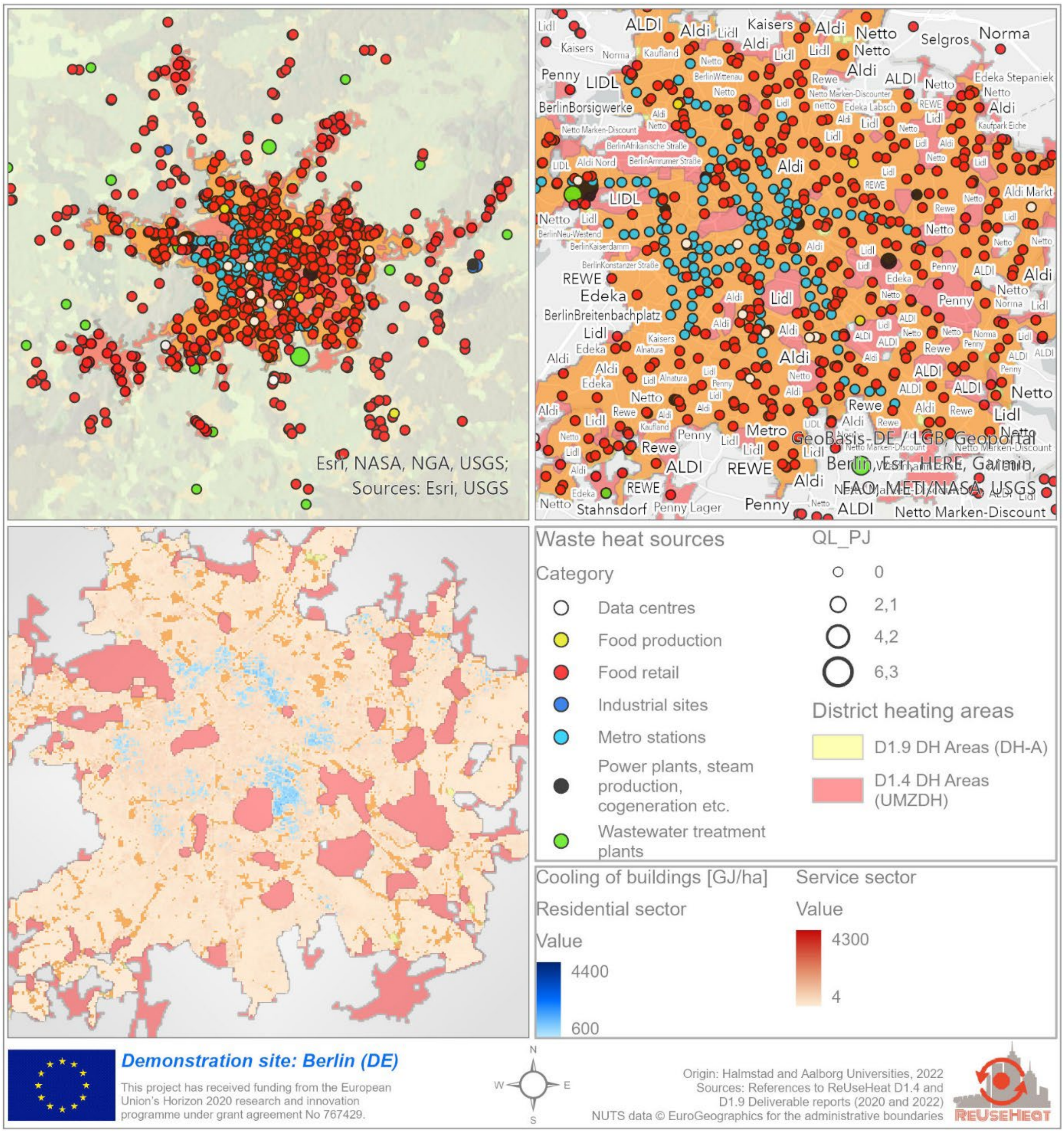

Figure 5. Available waste heat from unconventional and conventional sources in the demo-site of Berlin (DE), with 20-kilometre overview of point sources (top-left), city close-up with annotated point-sources (top-right), city close-up with rasterised sources (cooling of buildings in residential and service sectors) (bottom-left), and legends (bottom-right). The spatial extent of current district heating areas elaborated in the original work (D1.4) and in this update (D1.9) are both included for reference. Note that for the quantified point source legend, "0" indicates in the case of data centres "No data", otherwise values from close to zero and upwards to the next legend class.

2.2.1 Monitoring data

Before the demo-site in Berlin was abandoned, monitored data was retrieved from a tunnel in Berlin, including temperature and relative humidity from June 2021 to February 2022. Figure 6 shows the temperature data for the metro demo-site in Berlin. As expected, the temperature is lower in the winter and higher in the summer months. In June-August the temperatures are between 23°C and 26°C, while they drop to 11°C – 14°C in January.

Figure 6. Monitoring data in the form of platform temperature measurements from a nine-month period at the Berlin demo-site metro station.

Figure 7 shows the relative humidity for the same months as the temperature. The data shows that the average humidity is relatively stable around 50% in all months. The minimum is around 40% in the summer months while being lowest at 22% in December. The maximum relative humidity is between 60 – 80%.

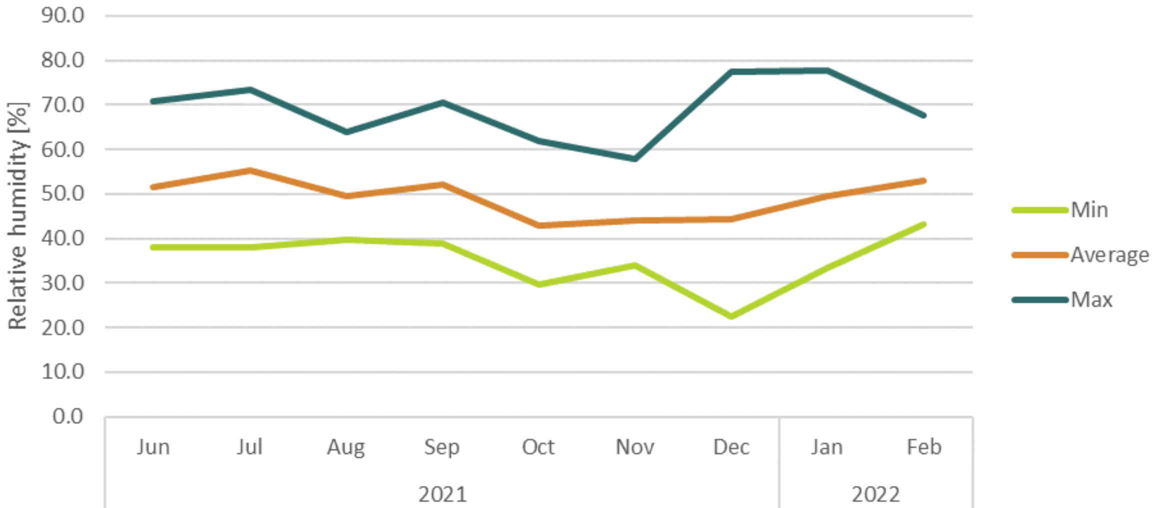

Figure 7. Monitoring data in the form of platform relative humidity from a nine-month period at the Berlin demo-site metro station.

2.2.2 Questionnaire responses

In terms of questionnaire responses related to metros, only two were collected. The data for these are presented in Table 7. Both have temperature levels between 20 – 40°C and low energy volumes of less than 36 gigajoule per year (less than 10 MWh/year).

Table 7. Data reports from two metro stations gathered by means of the ReUseHeat online questionnaire, by fluid type used in heat recovery, fluid temperatures, and annually available waste heat volumes

Nr	Fluid type	Temp. ºC	Temp. max ºC	Temp. Min ºC	Energy volume [GJ/a]	Energy volume [MWh/a]
1	Water	20 - 40	25	25	< 36	< 10
2	Air	20 - 40	25	15	< 36	< 10

2.3 Cooling of service sector buildings (Madrid)

The excess energy (heat) needed to be removed from a building to maintain a given indoor temperature is equal to its cooling demand. On this fact rests the basic assumption by which the modelling of available and accessible waste heat potentials for this source category has been conceived (similarly for cooling of residential sector buildings). This removal of heat, or supply of cold, can in practice be arranged in several various ways, depending on the scale of the application. In this work, central cooling devices constitutes the considered technology.

To give a brief account of the fundamental principles used in the modelling of this source category (for the full account, kindly see the original work), it involves basically just two main steps: determination of rejected heat from central cooling devices and calculation of waste heat potentials. Rejected heat from central cooling devices, such as CAC (central air-conditioning) units, in service sector buildings is assumed to be recovered in the temperature range between 30°C and 40°C, as outlined in Table 2.

In the first step, for the calculation of rejected heat from the anticipated central cooling devices, an average EU28 SEER value of 3.128 [35] has been used uniformly in this modelling. The SEER value has been applied as representing, on average, the practical COP for a refrigeration process ($COP_{R,p}$), which may be defined as the heat absorbed from the cooling space (Q_L) divided by the work input to the compressor, according to [22]:

$$COP_{R,p} = \frac{Q_L}{W} \qquad [-] \qquad (7)$$

From this, in combination with the general energy balance for refrigeration cycles, as expressed in Equation (1), the rejected heat from the cooling process (Q_H), may be expressed according to:

$$Q_H = Q_L\left(1 + \frac{1}{COP_{R,p}}\right) \qquad [-] \qquad (8)$$

In accordance with Equation (8), consequently, total volumes of rejected heat from the first step are here considered equivalent to available waste heat to be introduced to the second stage, which corresponds to the anticipated heat recovery by large-scale heat pumps. As for the other elaborated source categories, the sum of the available waste heat and the electric energy introduced in the heat pump conversion process resembles the final output, the accessible waste heat from cooling of service sector buildings.

As for the spatial representation of the service (and residential) sector waste heat potentials, both of which are here represented geographically by raster grids, various raster calculations were used which involved, among other, input data on sector floor areas in combination with e.g., numerical data on national shares of cooled surface areas. One recognised shortcoming in this respect is that the model distributes such national shares of cooled surface areas evenly among the whole population of sector grid cells, which does not reflect that such shares likely are much higher in high density inner city urban areas, than at less dense locations.

For this source category, Madrid, Spain, is the host of the associated demo-site: a city hospital at which rejected heat from a central cooling system is recovered and utilised by means of a booster heat pump serving an on-site local thermal network. Figure 8 presents the local waste heat potentials for the Madrid metropolitan area according to the map design used also for the other demo-sites. As can be seen, at this south-European location, the available waste heat potential from cooling of buildings in both service and residential sectors, is markedly more pronounced compared to the other locations. This is reflective of course of generally higher cooling demands in buildings found at these latitudes. For this particular reason, having a city like Madrid to represent this source category, is quite appropriate (see by the way also the corresponding raster map for demo-site Bucharest, where similar tendencies are visible).

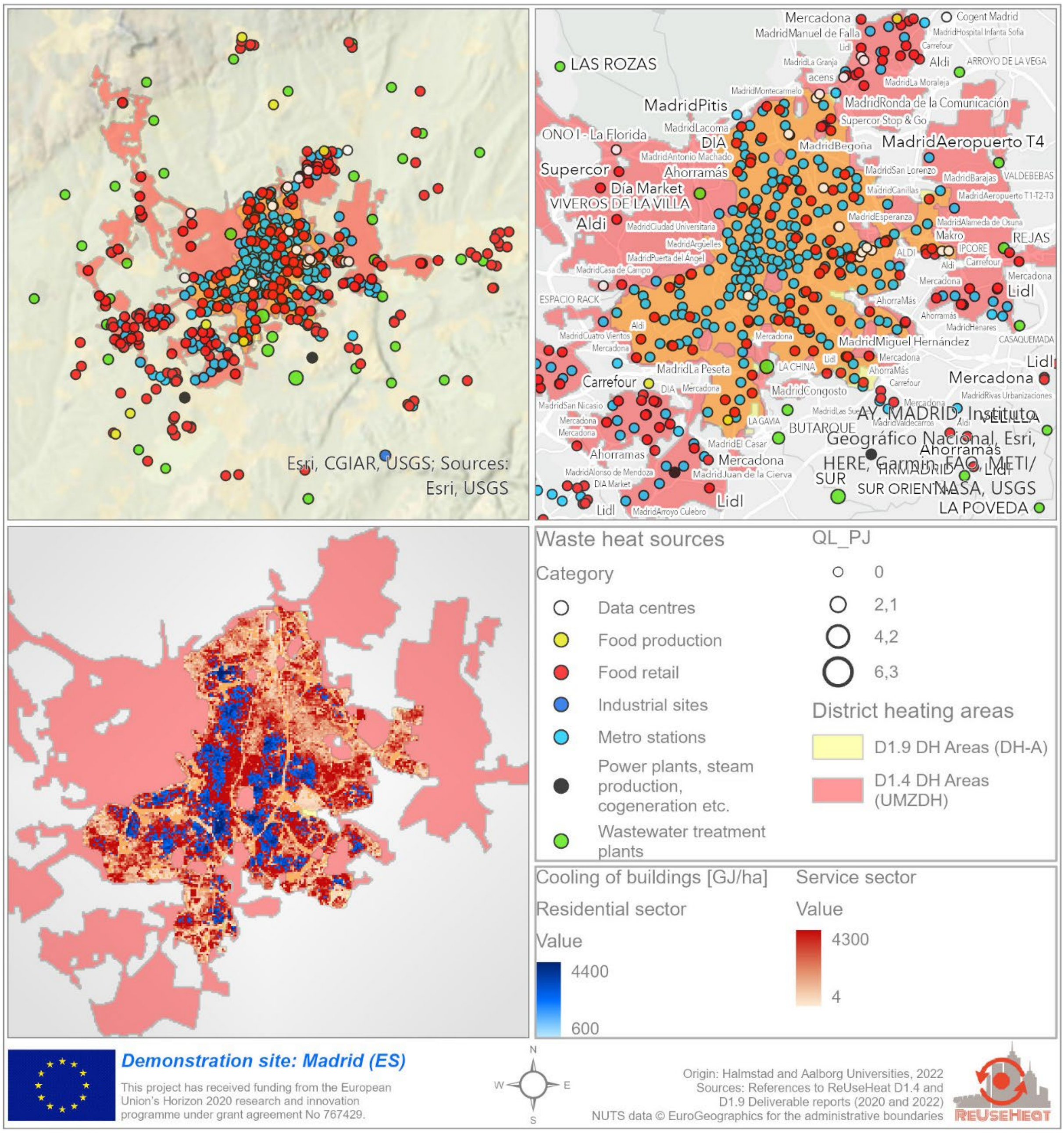

Figure 8. Available waste heat from unconventional and conventional sources in the demo-site of Madrid (ES), with 20-kilometre overview of point sources (top-left), city close-up with annotated point-sources (top-right), city close-up with rasterised sources (cooling of buildings in residential and service sectors) (bottom-left), and legends (bottom-right). The spatial extent of current district heating areas elaborated in the original work (D1.4) and in this update (D1.9) are both included for reference. Note that for the quantified point source legend, "0" indicates in the case of data centres "No data", otherwise values from close to zero and upwards to the next legend class.

2.3.1 Monitoring data

At the Madrid demo-site hospital, the heat recovery system has been monitored since January 2022 and thus three months of measurement data from full-time operation has been retrieved for this report (from 2022-01-01 to 2022-04-04). The data has been retrieved for both energy quantities and temperature levels based on 15-minute intervals.

Table 8 shows the monitoring data from the hospital in Madrid as monthly maximum, minimum, and average, values. The return temperatures at the heat pump are between 5.6°C and 14.3°C while the supply temperatures are between 19.2°C and 76.2°C. The average temperatures are around 10 – 12°C for return and 52 – 63°C for the supply. The COP values are between 2.6 – 3.4 in the dataset. However, the low COP 2.6 is in April, where only a few days of data has been collected. In the other months the COP is 3.0 or higher. Noteworthy, a monthly average available waste heat value of 0.81 terajoule is suggested by this data (corresponding to some 225 megawatt-hours per month).

Table 8. Monitoring data from three months of full-time operation (January to March) at the Madrid demo-site hospital

Heat from heat pump					
	Jan	Feb	Mar	Apr	Average
TJ	1.09	1.01	1.05	0.10	0.81
MWh	303.6	280.5	290.5	29.1	225.9
Return					
Return Max ºC	14.1	14.3	13.9	11.7	13.5
Return Average ºC	11.3	10.4	10.2	10.6	10.6
Return Min ºC	7.8	5.6	8.3	9.8	7.9
Supply					
Supply Max ºC	76.2	71.2	66.7	64.3	69.6
Supply Average ºC	52.8	56.4	56.8	63.7	57.4
Supply Min ºC	22.6	27.4	19.2	61.2	32.6
Electricity use heat pump					
	Jan	Feb	Mar	Apr	
TJ	0.32	0.33	0.35	0.04	0.26
MWh	90.0	90.9	98.5	11.0	72.6
Average COP	3.4	3.1	3.0	2.6	3.0

2.3.2 Questionnaire responses

Table 9 shows data for the service sector buildings that was collected through the ReUseHeat questionnaire. In the dataset, only one facility was collected, and it is unclear what type of service sector building this represents. The heat source is air as it is based on space cooling, and the temperature level is between 40 – 60°C.

Table 9. Data report from one service sector building gathered by means of the ReUseHeat online questionnaire, by fluid type used in heat recovery and fluid temperatures

Nr	Fluid type	Temp. ºC	Temp. max ºC	Temp. Min ºC
1	Air	40 - 60	50	40

2.4 Waste water treatment plants (Nice)

Regarding the last and final source category, that of waste water treatment plants, the demo-site in French Nice intended to develop a dashboard in association with heat recovery from a waste water treatment facility in the city. However, another setup, instead using sea water as the available heat source, at another location (La Seyne-sur-Mer instead of Nice), has rendered this demo-site less relevant with respect to this report. As the mapping and modelling here is focused on waste water treatment as source category, no monitoring data has been considered from this demo-site.

The modelling of waste heat potentials from this source category is based on the fundamental condition that external heat, in principle, never is added to sewage plant treatment processes. The major significance of this is that the heat content present in post-treatment sewage water should equate approximately to that heat content inherent in heated domestic hot water used in residential and service sectors. On this basis, and by combining site-specific load and design capacity data, available in the public "Waterbase-UWWTD_v6" waste water treatment plant database from the European Environment Agency [36], with a specially developed regression model incorporating some 20 Swedish instances where sewage water waste heat was recovered by heat pumps and utilised in district heating systems (for further references on the vast time-series data used in this context, see the original work), the modelling of available heat as a function of such design capacities was made feasible.

In terms of temperature levels of sewage water, an annual average temperature of 12°C for treated waste water flows was anticipated in this modelling, while actual temperatures are expected to be found in the interval of 8°C to 15°C (as outlined in Table 2 above).

To maintain our mode of presentation, despite the lack of monitoring data for this source category, Figure 9 presents the potential mapping outputs for the beautifully located coastal city of Nice. This map also provides one more good example of the differences between the original (UMZDH) and the update (DH-A) datasets used to spatially represent current district heating areas, which for the city of Nice is considerable.

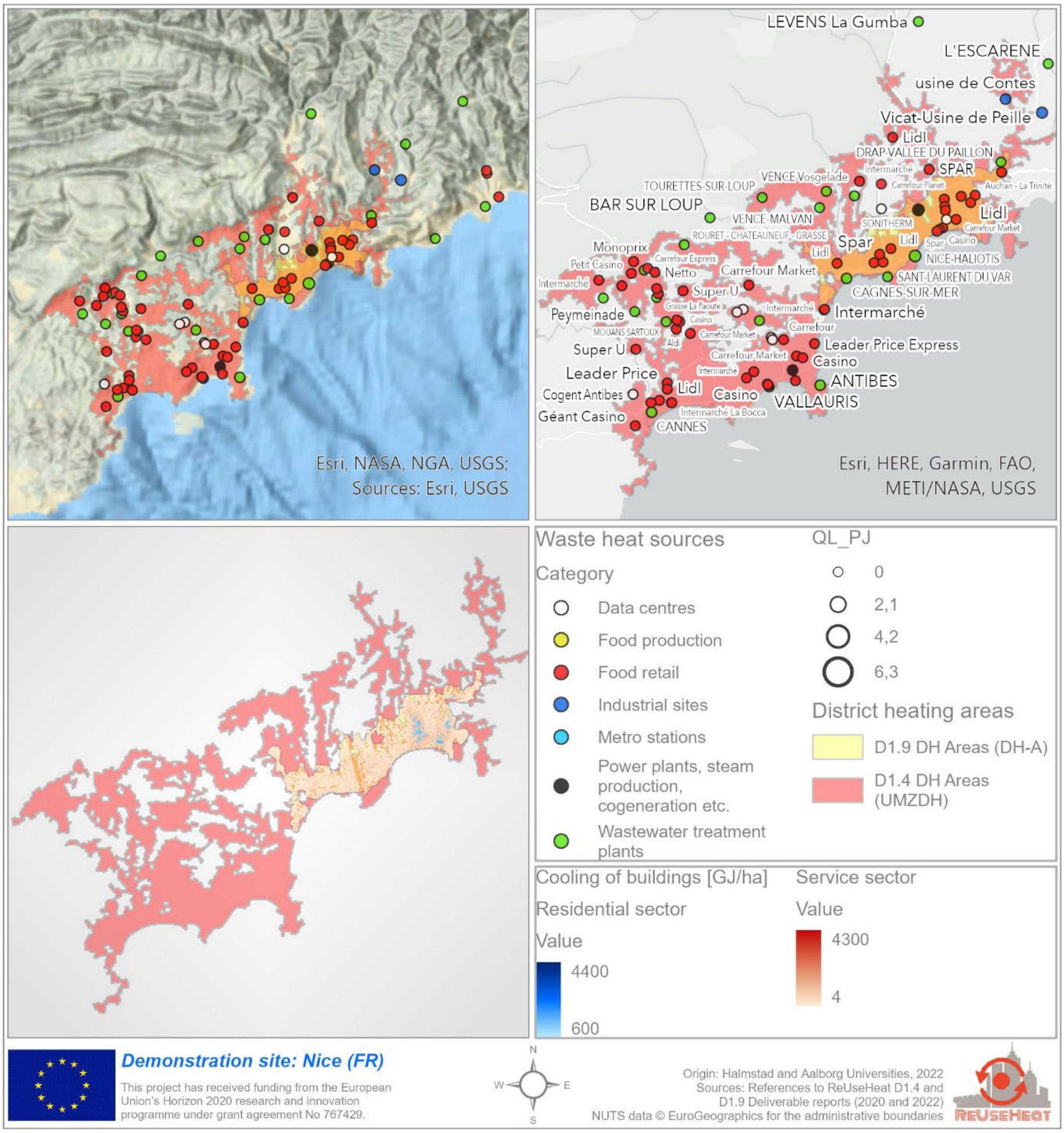

Figure 9. Available waste heat from unconventional and conventional sources in the demo-site of Nice (FR), with 20-kilometre overview of point sources (top-left), city close-up with annotated point-sources (top-right), city close-up with rasterised sources (cooling of buildings in residential and service sectors) (bottom-left), and legends (bottom-right). The spatial extent of current district heating areas elaborated in the original work (D1.4) and in this update (D1.9) are both included for reference. Note that for the quantified point source legend, "0" indicates in the case of data centres "No data", otherwise values from close to zero and upwards to the next legend class.

2.4.1 Monitoring data

As the Nice demo-site was not realised with a waste-water treatment plant application, there is no relevant monitoring data available for this report.

2.4.2 Questionnaire responses

Figure 10 shows the data gathered on waste water treatment though the ReUseHeat questionnaire. The dataset includes information on eight different waste water treatment facilities. Two of them are based on water at temperatures between 20 and 27°C while the others are based on air suply to active sludge at temperatures between 75°C and 99°C.

Table 10. Data reports from eight waste water treatment plants gathered by means of the ReUseHeat online questionnaire, by technology, fluid type, fluid temperatures, and annually available waste heat volumes

Nr	Technology	Fluid type	Temp. ºC	Temp. Max ºC	Temp. Min ºC	Energy volume [TJ/a]	Energy volume [MWh/a]
1	Sewage	Water	20	27	13	172.8	48,000
2	Sewage	Water	20	25	8		
3	Air supply to activated sludge process	Air	85			0.972	270
4	Air supply to activated sludge process	Air	98			0.972	270
5	Air supply to activated sludge process	Air	85			0.504	140
6	Air supply to activated sludge process	Air	99			0.702	195
7	Air supply to activated sludge process	Air	81			0.378	105
8	Air supply to activated sludge process	Air	75			0.324	90

2.5 Updated demo-site potentials

To sum up, a closer look at the five demo-sites, as presented with respect to numbers in Table 4 (above) and in terms of updated waste heat potentials in Table 11 below, reveals that, from a total of 1866 waste heat point sources (plus that from the two rasterized sources; cooling of residential and service sector buildings), just about one hundred petajoule (99.5), or some ~28 terawatt-hours, of available waste heat has been found to be located inside or within 20 kilometres of the perimeters of current district heating areas, according to their updated definition.

The two largest cities among these five, Madrid and Berlin, also host the largest relative shares of the potentials, at 37% (36.5 petajoule, or 10.1 terawatt-hours) and 31% (30.7 petajoule, or ~8.5 terawatt-hours) respectively. At 5% of the total demo-site potential, Nice is the smallest of the five with an assessment at 5.4 petajoule of available waste heat (1.5 terawatt-hours), which is still a considerable amount of annual energy when referring to building heat demands.

*Table 11. Summary of available waste heat at the five demo-sites, inside or within 20 kilometres of current district heating areas. Note: * indicates only inside current district heating areas*

Demo Name	DC (65%) [PJ/a]	MS [PJ/a]	FP [PJ/a]	FR [PJ/a]	Res. Sector* [PJ/a]	Ser. Sector* [PJ/a]	WWTP [PJ/a]	Conv. (25%) [PJ/a]	Total	Share
Berlin	3.8	1.2	0.016	2.0	1.2	1.8	8.5	12.1	30.7	31%
Brunswick	-	-	0.003	0.4	0.0	0.1	1.2	12.2	14.0	14%
Bucharest	2.0	0.5	0.007	0.4	1.9	3.0	2.2	2.8	12.8	13%
Madrid	6.4	2.4	0.019	0.9	5.3	13.2	7.2	1.1	36.5	37%
Nice	1.7	-	-	0.2	0.1	0.4	1.7	1.3	5.4	5%
Total	13.9	4.1	0.045	4.0	8.5	18.5	20.8	29.6	99.5	100%
Share	14%	4%	0.04%	4%	9%	19%	21%	30%	100%	

As also visible in Table 11, 29.6 petajoules (30%) of the total potential originates in so called conventional sources (energy intensive industries, power and Waste-to-Energy plants), which is expected since these sources are associated with larger unit-magnitudes compared to unconventional sources (note that this is the found case here despite only referring to 25% of maximum theoretical potentials). Waste water treatment is the second largest source in the total (21%), followed by the service sector at 19%.

Regarding monitoring data gathered from the demo-sites, we have learned that the temperature levels anticipated in the potential modelling, as outlined in Table 2 above, are in general accordance with those found in the reported data. With respect to technical configurations, especially regarding how available waste heat is actually recovered from the original heat sources (heat pump conversion type), the demo-site in Brunswick is indicative of the use of a two-stage, rather than a one-step, setup. It is likely that heat pump operation is more effective, and manageable, when the evaporator is exposed to a liquid flow, rather than an air flow. Although no monitoring data was gathered for metro stations, it would not be unreasonable to expect similar applications within that source category as well. The 161 terajoule average per data centre and year available waste heat quanta derived from the questionnaire responses (Table 6) stands out as particular reference for our generic modelling.

3 Model updates

This section includes three subsections, one for each of the three model updates which have been elaborated in this work. The first subsection addresses the data centre model update, which consists primarily of the acquisition and preparation of a new (and later date) version of the original dataset, as well as adaption to later year statistics on European final consumption of electricity for these purposes. The second subsection presents the metro station model update, which includes, among other, the introduction of a traffic intensity parameter for a sample set of stations. In the third subsection, an account is given regarding the spatial analyses performed to derive utilisation potentials with regards to current district heating areas.

3.1 Data centres

The original plan intended for the assessment of available waste heat from data centres was, as also described in the original work, to use site-specific data on installed IT-equipment capacities together with e.g., information on annual operating hours and assessed shares of electricity used for IT-equipment etc. Despite quite some work to attain such site-specific information, as for example though the European Commission Code of Conduct for Energy Efficiency in Data Centres initiative [37, 38], it proved difficult within a sector characterised by confidentiality and sensitive activity to actually get access to such detailed (and supposedly revealing) data. Not even after the hopeful acquisition of a commercial dataset, the 2018 Data Center Map assembly [39, 40], which also didn´t contain sufficient information on the sought quantitative data parameters to fulfil these intentions, was it possible to realise the initial approach, why, eventually, it had to be abandoned.

3.1.1 Final consumption of electricity

To still proceed, an alternative approach was adopted which was based on the idea to use statistical information on member state total final consumption of electricity, in combination with literature references on historical developments of data centre electricity use (as fractional shares of such totals). To this end, literature reviews gave that, globally, data centres accounted for 1.1 – 1.5% of the world’s total final electricity consumption already in 2010 [41], and that, by cross reference to the IEA (International Energy Agency) energy statistics for the same year [42], this indicated a total data centre electricity consumption volume in the interval of 218 – 298 TWh (785 – 1073 PJ) for the given year.

For Europe, Bertoldi et al. [43], assessed that 56 TWh (201.6 PJ) of electricity was used in data centres during 2007. In a more recent publication [44], Avgerinou et al. presented a summary compilation of different estimations made of data centre final consumption electricity use during the last two decades, a compilation that is freely reproduced and further elaborated in Table 12. Note that the two far-right columns in this table have been added to the original table and that EU28 final consumption of electricity for 2020 refers to the volume used in this update [45].

*Table 12. European data centre final consumption electricity use as estimated in various sources and compiled by Avgerinou et al. in [44]. EU28 final consumption electricity use as reported for 2016 in [42] and for 2020 in [45]. Ad hoc share for 2020 marked with: * (previous share stated at 3.66%).*

Year	Reference	Source	Data Centre FC Electricity [PJ/a]	EU28 FC Electricity (IEA) [PJ/a]	Share [%]
2000	Koomey (2011)	[41]	65.9	9104.3	0.72%
2005	Koomey (2011) and Whitehead (2014)	[41, 46]	148.7	10027.3	1.48%
2007	Bertoldi (2012)	[43]	201.6	10269.7	1.96%
2010	Whitehead (2014)	[46]	261.0	10233.2	2.55%
2020	Bertoldi (2012)	[43]	374.4	9665.7[a]	*3.87%

[a] This volume refers to Eurostat data for year 2020. Note that in this EU28 total, data for the United Kingdom refers to 2019.

By plotting the percentage shares given in Table 12 in graphs, as in Figure 10, and fitting curves to these numbers by regression, the share of data centre final consumption electricity use out of total volumes may be anticipated for years other than those known, and with respect to different statistical sources. In the original work, where these statistics referred to IEA 2016 [42] (here reproduced by use of Eurostat 2016 data [47]) and the model year 2016 (at left in Figure 10), a share factor of 3.50% was found and used in the original modelling. For this update (at right in Figure 10), 2020 statistics from Eurostat [45] has been used to estimate the 2020 model year share factor, found according to a linear fit at 3.96%.

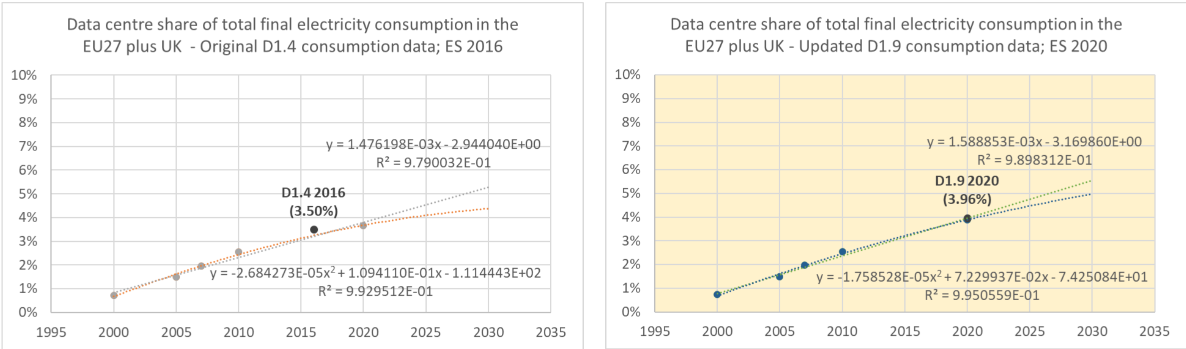

Figure 10. European data centres average share of electricity use out of total final consumption of electricity as estimated in various sources and compiled by Avgerinou et al. in [44]. At left, related to the original D1.4 Eurostat consumption data for 2016 [47] and the anticipated corresponding 3.50% factor used the previous assessment. At right, related to Eurostat consumption data for 2020 [45] and the anticipated D1.9 share factor at 3.96%.

As also presented in Figure 10, second order polynomial curves were also fitted in both instances to provide reference, since in both instances these curves were characterised by somewhat higher coefficients of determination. As can be seen, the polynomial curves both display flattening-out tendencies beyond 2020 and onwards. Whether this could be interpreted as an emerging data centre market saturation in the coming years remains an open question from these inquiries.

3.1.2 Data Center Map 2020

Table 13 presents an overview of the two data centre datasets used in this work.

Table 13. Key metrics on EU28 data centres from the original work (D1.4) and the model update (D1.9) Data Center Map datasets. Sources: [19, 40, 45, 47]

	Original work (D1.4)			Model update (D1.9)		
CC	Data centres [n]	Total El FC (2016, ES) [PJ]	DC El FC at 3.5% of total FC (2016, ES) [PJ]	Data centres [n]	Total El FC (2020, ES) [PJ]	DC El FC at 3.96% of total FC (2020, ES) [PJ]
AT	17	223	7.8	23	220	8.7
BE	32	295	10.3	32	285	11.3
BG	20	104	3.6	25	105	4.2
CY	13	16	0.6	13	16	0.6
CZ	24	202	7.1	24	207	8.2
DE	203	1863	65.2	222	1727	68.4
DK	29	112	3.9	31	112	4.5
EE	10	26	0.9	10	29	1.2
EL	14	192	6.7	14	171	6.8
ES	59	837	29.3	64	792	31.4
FI	18	291	10.2	22	277	11.0
FR	147	1593	55.7	157	1487	58.9
HR	5	55	1.9	7	55	2.2
HU	8	134	4.7	9	145	5.7
IE	22	92	3.2	24	102	4.0
IT	67	1030	36.0	70	991	39.3
LT	11	35	1.2	12	37	1.5
LU	15	23	0.8	15	22	0.9
LV	17	23	0.8	17	23	0.9
MT	8	8	0.3	8	8	0.3
NL	97	380	13.3	110	388	15.4
PL	31	478	16.7	32	494	19.6
PT	26	167	5.8	26	167	6.6
RO	48	156	5.5	51	159	6.3
SE	53	459	16.1	50	443	17.6
SI	7	47	1.6	8	47	1.8
SK	14	90	3.1	14	86	3.4
UK	254	1094	38.3	270	1068	42.3
EU28	1269	10023	350.8	1360	9666	383.0

As can be seen in Table 13, the model update version of the Data Center Map dataset [19] contains records of 1360 data centres within the EU28 with geographical coordinates given (1269 in the original). Total final consumption of electricity in the European Union decreased from 2016 (at ~10.02 EJ per year) to 2020 (~9.67 EJ per year (given the inclusion of 2019 data for the United Kingdom)). This total final consumption decrease is counteracted, with respect to found electricity used in data centres, by two parallel factors, on the hand, the 7.2% increase in count (from 1269 to 1360), and on the other, by a 2020 share factor at 3.96% relative to the original at 3.50%. Hereby, the total anticipated 2020 final consumption volume of electricity used in EU28 data centres was found at 383 petajoules, a 9.2% increase relative to the 2016 volume assessed at 350.8 petajoules.

To provide a visual overview of the two data centre datasets, the map in Figure 11 presents their point source locations. In this map, it may be seen where previous data centres are no longer and where new ones have become operational. Note, that an additional 50 data centres were part of the acquired update dataset (totalling at 1410 for the EU28), however, these were not associated with any geographical coordinates and were therefore excluded from the model update.

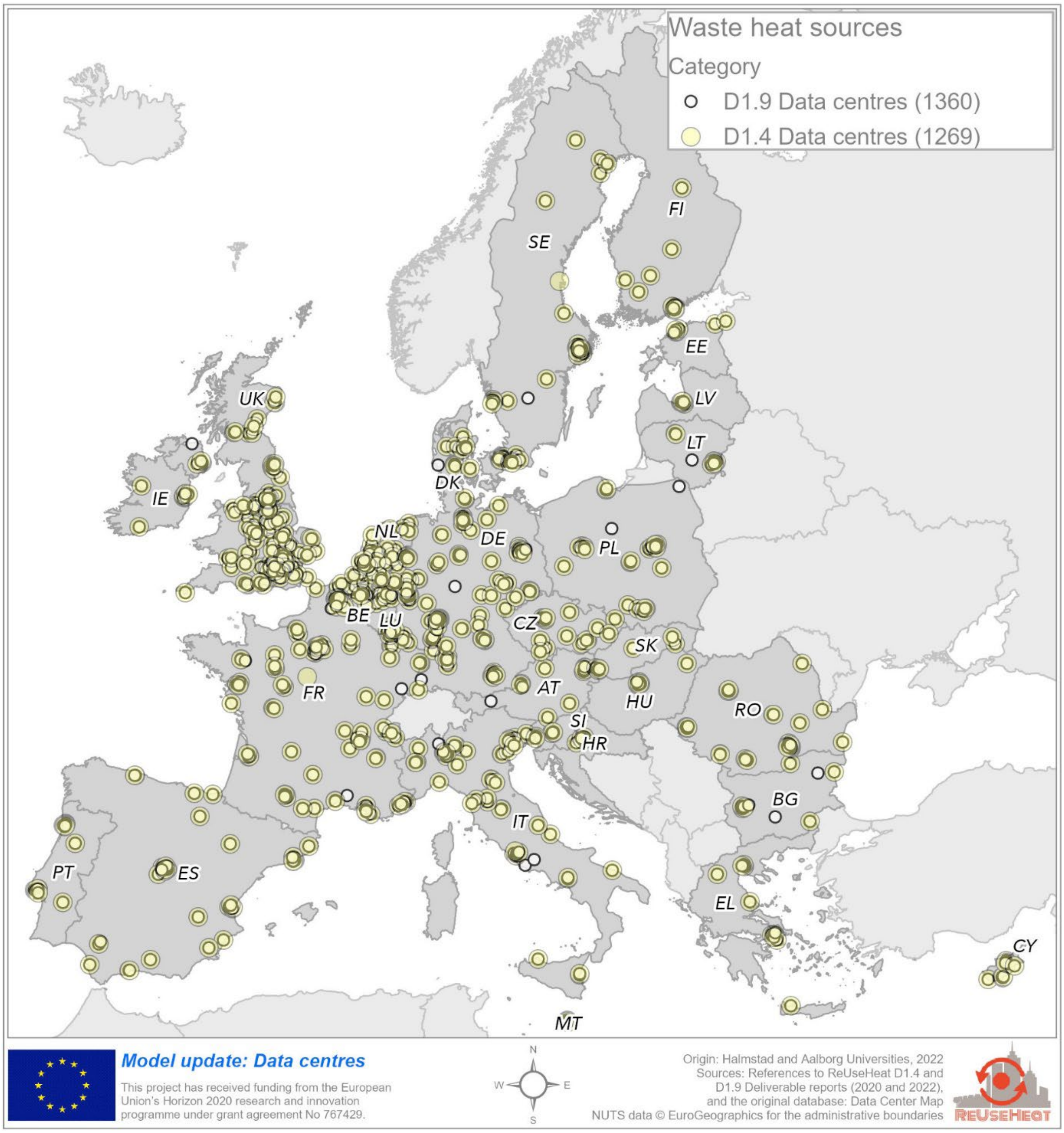

Figure 11. Map overview of the two data centre datasets used in the original work (D1.4) and the model update (D1.9) with respect to location and total count.

3.1.3 Updated data centre potential

Based on the above stated circumstances, the waste heat potential from European data centres have been modelled on the member state national level only. Potentials of available waste heat constitute 65% of final consumption electricity volumes used in data centres (in alignment with the original modelling), volumes which are established as 3.96% shares out of total national final consumption of electricity for the year 2020. The modelling further assumes that all cooling processes of IT-equipment in these data centres are performed by means of air-cooling systems. In another context, given the rapid development and extended use of water-cooling systems for data centres, this assumption should perhaps be reconsidered.

Table 14, outlines the available and the accessible annual waste heat volumes estimated for all 1360 facilities. As can be seen, the EU28 total available waste heat volume amounts to some 248.9 petajoule (previous assessment at 228.0 petajoules), which is reflective of the 9,2% relative increase also for the total final consumption of electricity in the EU28 for the same period. Correspondingly, at practical COP of 3.0, 373.4 petajoules of annual energy constitute the full accessible EU28 waste heat potential according to the performed modelling (342.0 petajoules in the original).

Table 14. Available waste heat as 65% of final consumption electricity used in 1360 EU28 data centres and accessible waste heat at practical COP of 3.0 for the 2020 model update. Anticipated annual average waste heat volumes per facility (indicative only)

CC	QL (65%) [PJ]	QH COP3.0 [PJ]	*QL by facility (65%) [TJ/DC]*	*QH by facility COP3.0 [TJ/DC]*
AT	5.7	8.5	*247*	*370*
BE	7.3	11.0	*230*	*344*
BG	2.7	4.1	*109*	*163*
CY	0.4	0.6	*31*	*47*
CZ	5.3	8.0	*223*	*334*
DE	44.5	66.7	*200*	*301*
DK	2.9	4.3	*93*	*140*
EE	0.8	1.1	*75*	*113*
EL	4.4	6.6	*315*	*472*
ES	20.4	30.6	*319*	*478*
FI	7.1	10.7	*324*	*486*
FR	38.3	57.4	*244*	*366*
HR	1.4	2.1	*202*	*302*
HU	3.7	5.6	*415*	*622*
IE	2.6	3.9	*110*	*164*
IT	25.5	38.3	*365*	*547*
LT	1.0	1.4	*80*	*120*
LU	0.6	0.9	*38*	*57*
LV	0.6	0.9	*36*	*53*
MT	0.2	0.3	*27*	*41*
NL	10.0	15.0	*91*	*136*
PL	12.7	19.1	*398*	*597*
PT	4.3	6.4	*165*	*248*
RO	4.1	6.1	*80*	*120*
SE	11.4	17.1	*228*	*342*
SI	1.2	1.8	*150*	*225*
SK	2.2	3.3	*158*	*237*
UK	27.5	41.3	*102*	*153*
EU28	248.9	373.4	*183*	*275*

In the two far-right columns of Table 14 are indicated what is assessed as specific corresponding quantities per site, on average. These numbers are included here for reference, however, since the modelling has had access to no actual site-specific information (such as floor areas, installed capacities etc.), no distinction is made regarding actual site sizes, which may vary significantly. For this reason, these number have been displayed in italics, meaning that they are indicative only.

Nonetheless, we find it noteworthy to observe that the found EU28 average at 183 terajoule of available waste heat per data centre and year (176 terajoule in the original work), is rather well in correspondence with the questionnaire average presented for 67 instances with absolute numbers given in subsection 2.1.2 above; an average which was found at 161 terajoule per datacentre and year on average. In this particular instance therefore, we conclude that data generated by particular methods can indeed verify data generated by generic methods. Hereby, since two separate approaches are indicative of the same order of magnitude, we may assume specific available waste heat volumes from EU28 data centres to be found, on average, in the range of 45 – 50 gigawatt-hours per year.

3.2 Metro stations

The original work to model waste heat potentials from metro stations consisted first and foremost of a laborious undertaking to build – manually, by gathering official public transport maps and other useful information sources for each respective city metro system [48-84] and by georeferencing these [85] – a comprehensive database with EU28 metro stations, including their geographical coordinates, their names, the number of lines frequenting them, and several other attributes. Secondly, a general heat balance model incorporating among other location-specific ambient temperature and air humidity data, was created whereby to calculate station-level annual waste heat volumes to be used for the potential assessment.

By this approach, the original work could indeed present first-of-its-kind metro system potential assessments for the EU28, and also so separately for each of the member states among which metro stations had been found and mapped. Potential assessments could even be presented at the given station level, according to what was called "city-station-averages", but not, however, as unique station-specific potentials. In the original work, this model limitation was recognised as "one significant drawback in the performed modelling is that the assessed waste heat potentials for each station have had to build on city average values, i.e., that every station in a city has been assigned the same potential" (page 47 in [16]).

Although the original intention for the modelling had been to estimate unique potentials for each given station, a lack of appropriate data parameters that could serve such a purpose, such as for example number of persons entering and exiting a platform on a daily, weekly, or monthly basis, or, for that matter, any other suitable data parameter by which a traffic intensity indicator could be derived, rendered these ambitions futile at that stage. Instead, as stated above, the model capacities were calculated as station averages, based on local climate conditions for each respective city, and then distributed uniformly to all stations within each given city.

3.2.1 Traffic intensity parameter

For this model update, work has been done to solve this problem conceptually by identifying a possible metric on which basis the establishment of such a traffic intensity parameter can be facilitated, and by developing scripts whereby to retrieve related data, further, to test the concept itself, and to bring into this report at least a few samples with new results from this undertaking. The identified metric consists in the simple notion of how many trains that pass a metro station during a given period of time.

The number of passing trains is a measure that indicates how many trains that pass a metro station within a time interval. In this context, six of the 37 cities with metro systems in operation (London, Madrid, Berlin, Stockholm, Brussels, and Lisbon) which were part of the metro database developed in the original work (for further detail, see Table 17), were selected as primary samples for this update. Together, the metro systems in these six cities include 633 underground metro stations (corresponding to 32% of the 1994 database total count of underground metro stations, see further also Table 18).

Depending on the availability, two main approaches have been applied to gather data. One is to write MATLAB codes to repetitively request the needed data and get it through API' s (for London and Berlin). The other approach has been to find the corresponding timetables or schedules and use Excel spreadsheets to perform calculations (for the other four cities). The data source of both approaches is the official transport and metro websites. Table 15 summarizes the used methods and the data sources.

Table 15. Methods, tools, and data sources of traffic intensity data for the six sample cities

City	Method\Tool	Data source
London	API, MATLAB	[86]
Madrid	MS Excel	[87]
Berlin	API, MATLAB	[88]
Stockholm	MS Excel	[89]
Brussels	MS Excel	[90]
Lisbon	MS Excel	[91]

For Madrid, the procedure consisted of gathering intervals between trains for each metro line by days of the week and hours of the day and then enumerating the passing trains from each station according to the lines it serves. The same method has been utilized for Stockholm, Brussels, and Lisbon. The intensity data for London and Berlin has been calculated by first determining the routes for lines, then counting the departures for routes, and finally computing the total departures for each station regarding the routes encompassing that station. Table 16 gives an overview of the intensity results.

Table 16. Summary overview of the annual, daily, and hourly number of trains passing through the metro stations of the six sample cities

City	Annual intensity		Daily intensity		Hourly intensity		Hourly intensity in one direction	
	Total	Per station (average)	Total	Per station (average)	Total	Per station (average)	Total	Per station (average)
London	74,880,577	281,505	205,152	771	8,548	32	4,274	16
Madrid	47,344,543	173,423	129,711	475	5,405	20	2,702	10
Berlin	27,598,376	160,456	75,612	440	3,150	18	1,575	9
Stockholm	13 254 560	132,546	36,314	363	1,513	15	757	8
Brussels	9,884,264	167,529	27,080	458	1,128	19	564	10
Lisbon	6,824,697	136,494	18,697	373	779	16	389	8

Figure 12 gives graphical view examples for three of the six sample cities.

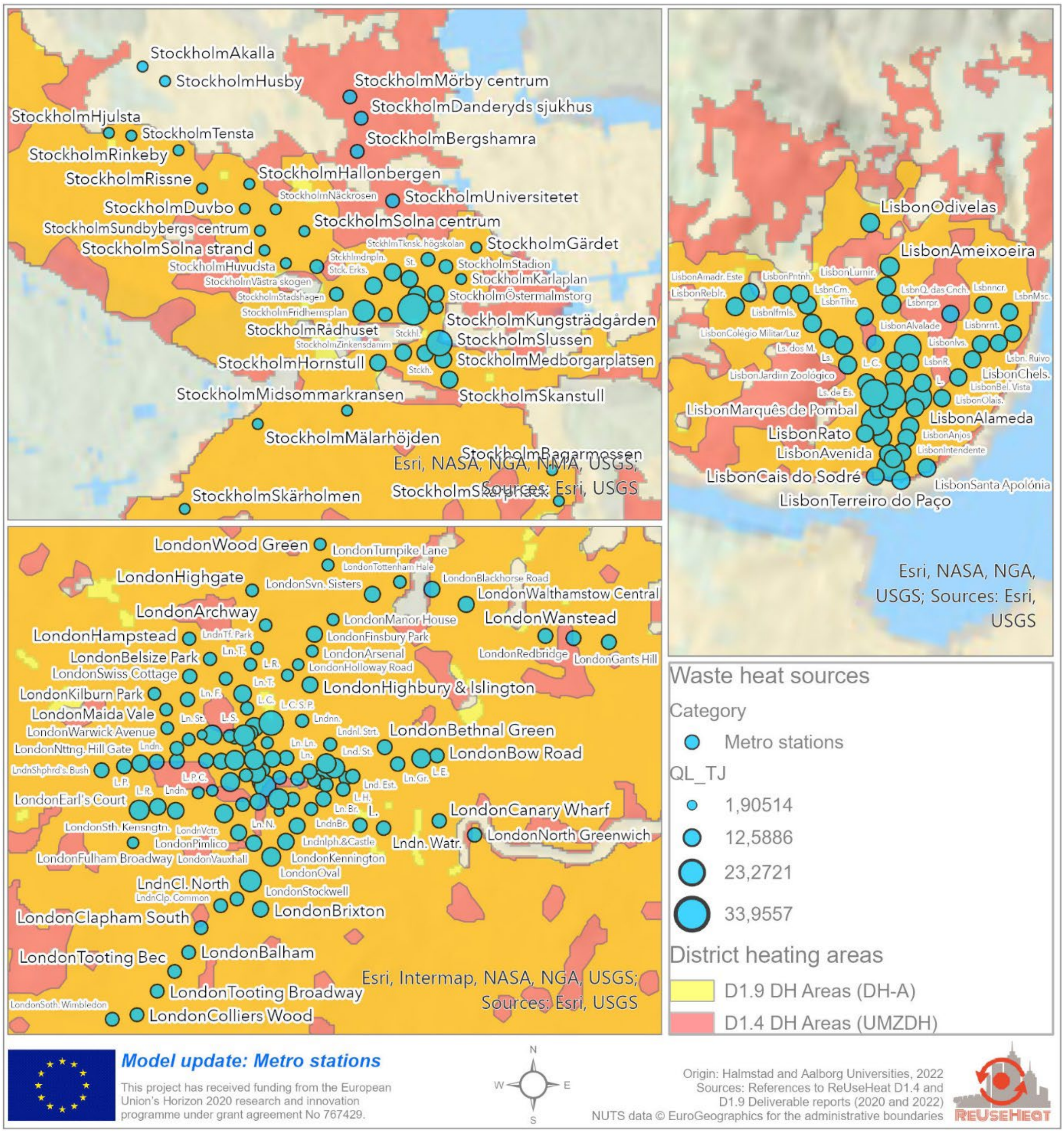

Figure 12. Map views of station-specific waste heat potentials derived by incorporating a traffic intensity parameter in the metro model.

The map views presented in Figure 12 (for Stockholm, Lisbon, and London) illustrates the significance of incorporating a traffic intensity parameter in this modelling, since, as can be seen, heavily frequented stations, which are expected to be associated with larger waste heat volumes than stations less frequented, are indeed allocated larger shares of available waste heat. The rendering of station-specific waste heat potentials in this manner, was performed as a final modelling step by calculating station-specific intensity factors, on the basis of total and average city-level intensities, by which corresponding fractions of the original "city-station-averages" could be allocated each unique station.

Hereby, total city and member state waste heat potentials from this source category, as modelled for all 37 cities, remains unaffected since the traffic intensity parameter merely redistributes total city potentials among its stations according to the assigned factors.

3.2.2 Metro model version 8

Since the focus in this report is directed towards model updates, the full detail of the development of the metro model, with its 37 cities (presented in Table 17 in resumé), will mainly have to be that already given in the original work [16]. Here, in this subsection, the intention is instead to describe the second aspects of the metro model update, where incorporating a traffic intensity parameter was the first, two model elements which together has brought the metro model to its eighth's version.

Table 17. Listing of the 37 metro cities included in the metro station database developed in the original work

Amsterdam	Budapest	Lisbon	Newcastle	Stockholm
Athens	Catania	London	Nuremburg	Toulouse
Barcelona	Copenhagen	Lyon	Paris	Turin
Berlin	Genoa	Madrid	Prague	Warsaw
Bilbao	Glasgow	Marseille	Rennes	Vienna
Brescia	Hamburg	Milan	Rome	
Brussels	Helsinki	Munich	Rotterdam	
Bucharest	Lille	Naples	Sofia	

This second aspect relates to temperature settings in the general heat balance model used to assess the waste heat capacities of metro stations, waste heat which is conceived as being derived from station platform and tunnel exhaust ventilation air shafts, in turn mainly generated by electricity used to drive train carriages and auxiliary systems, and, most profoundly, from heat dissipated upon braking as trains stop at a platform.

In this general heat balance model, as principally illustrated at left in Figure 13, heat exchange at the heat pump evaporator is thought to take place in an air-to-water configuration setup (i.e., from exhaust air to the liquid refrigerant media across the evaporator surface), at an uniformly applied average moist air volume flow rate, $\dot{V}$ (m^3/s) of 30 m^3/s, a value based on collected information from several references [92-97]. In the original work, the model allowed the passing exhaust air to be cooling no further than to 5°C, mainly to avoid air humidity depositing and forming ice on the evaporator surface.

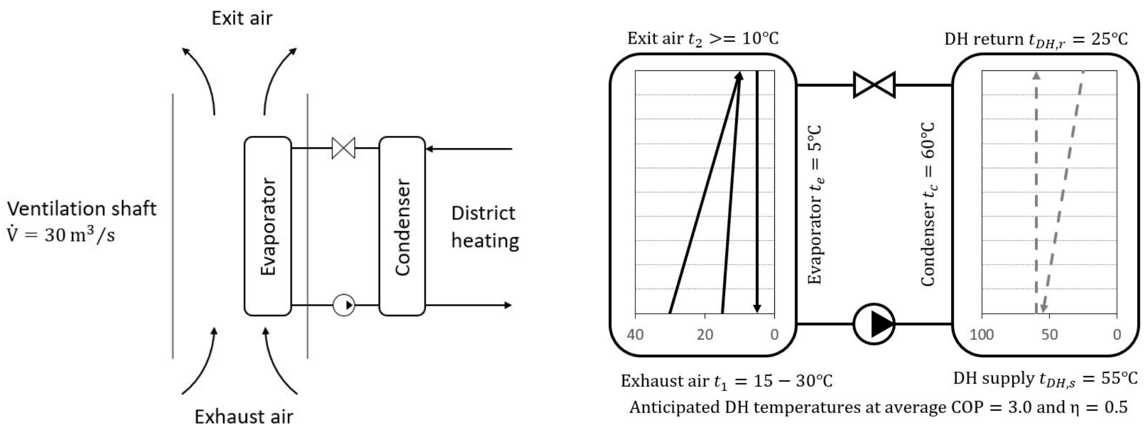

Figure 13. Principal outline of the conceived direct heat recovery from platform exhaust air at heat pump evaporator surfaces (left) and anticipated conversion and distribution temperature levels at an average COP of 3.0 at an overall Carnot efficiency of 0.5.

This model configuration represented however more or less the performance of an ideal, not a real, heat exchange process, since, in practise, a certain temperature difference will be present between escaping air and the evaporator as long as the area of this surface is not infinitely large. For the modelling in this update therefore, a lower limit at 10°C has been fixed for exit air (t_2 in Figure 13 at right). As for other model parameters, such as feasible temperature ranges of platform exhaust air temperatures (also visible in Figure 13 at right), which are modelled from 15°C (during winter) to 30°C (during summer), according to references [92, 98-104], no further changes have been made with reference to the original modelling.

Hereby, this update modelling anticipates, as in the original, the annual capacity utilisation of metro stations as following a “20/7” (twenty hours per day/seven days a week) operational regime for mechanical ventilation systems, which correspond to a capacity factor of 83.3% (no ventilation between 01:00 and 05:00). From this, annual operational hours are modelled as 7300 hours, evenly distributed from January to December.

As was mentioned for the data centre demo-site in Brunswick above, where a two-step configuration setup recovers heat from the air-cooling system in a primary water-to-water circuit, a similar note could be made here. When studying the configuration setup used in the London Underground heat recovery in Islington [105] for example, a fan-coil air-to-water heat recovery is installed prior to the heat pumps, so that heat the transfer at the evaporator occur between media in liquid form. Whether or not this is a more efficient heat recovery setup is here left unanswered, but future modelling of metro station waste heat potentials can perhaps benefit from using more detailed, rather than general, heat balance models, where, e.g., adding an air-to-water heat recovery stage before the heat pump could be one such element to consider.

3.2.3 Updated metro station potential

The total, updated, assessment of available waste heat from the 1994 considered underground metro stations in EU28 amounts to 21.0 petajoule annually (a substantial reduction compared to the 35.3 PJ anticipated in the original), as presented in Table 18. This reduction is reflective only of the second aspect of the model update described above. If considering an average COP of 3.0, the corresponding accessible waste heat potential is assessed at some ~32 petajoule (~8.8 terawatt-hours).

In specific numbers, an EU28 average metro station potential of available waste heat at approximately 10.6 terajoules is conceivable (~2.9 gigawatt-hours per station), albeit national variations are present. In terms of accessible waste heat at the default conversion efficiency (COP of 3.0), a per-station annual amount of 15.8 terajoule represents the EU28 average (some 4.4 gigawatt-hours), as detailed in the far-right column of Table 18. The waste heat potential from this source category, given these results, is not expected to have great impact on the continental level, however, at the local scale it may.

Table 18. Number of underground metro stations, available waste heat, and accessible waste heat at practical COP of 3.0. Anticipated annual average waste heat volumes per station (indicative only)

MS	Metro stations [n]	QL [PJ/a]	QH COP 3.0 [PJ/a]	QL by station [TJ/St.]	QH by station COP 3.0 [TJ/St.]
AT	48	0.5	0.7	9.7	14.6
BE	47	0.5	0.7	10.5	15.7
BG	29	0.3	0.4	9.6	14.4
CZ	53	0.4	0.6	7.7	11.5
DE	318	2.7	4.0	8.4	12.5
DK	9	0.1	0.1	8.0	12.0
EL	37	0.5	0.8	14.6	21.9
ES	407	4.8	7.2	11.8	17.7
FI	17	0.1	0.2	7.0	10.4
FR	441	4.7	7.0	10.6	16.0
HU	44	0.5	0.7	10.8	16.2
IT	214	2.9	4.3	13.5	20.3
NL	25	0.2	0.3	8.2	12.4
PL	27	0.2	0.3	8.3	12.4
PT	48	0.7	1.0	14.6	21.9
RO	45	0.5	0.7	10.8	16.2
SE	45	0.3	0.5	7.7	11.6
UK	140	1.2	1.8	8.5	12.7
Total	1994	21.0	31.6	10.6	15.8

3.3 Spatial analytics

In addition to the terminological distinction made in this work between available and accessible waste heat, explained above in subsection 1.3.2, an additional distinction is made also with regards to the geography of these potentials. For this end we distinguish here, on the one hand, between what we loosely refer to as "total potentials", and, on the other hand, between that which, quite loosely as well, we are referring to as "utilisation potentials". Where the former simply means the sum of waste heat, be it available or accessible, at unconstrained spatial contexts, the latter means spatial delineation by the above-described current district heating areas (see subsection 1.3.3). The logic behind this second distinction, if not self-evident, is the fundamental insight that waste heat cannot be recovered (in the large-scale sense) unless heat distribution infrastructures are in place for their recovery and reuse, hence, the label "utilisation potential".

As in the original work, the methodological approach whereby to determine this utilisation potential takes departure in the elaboration of a set of pre-defined distances, measured from the considered waste heat sources to the perimeters of current district heating areas, distances which represents heuristic and experience-based proxies for feasible waste heat recovery and transmission to such district heating areas. Whereas in the original, five pre-defined distances were part of the calculations (inside, within 2 kilometres, within 5 kilometres, within 10 kilometres, and, beyond 10 kilometres (outside)), a blend of the first two; the "inside or within 2 kilometres"-default setting, was used as the main results metric. In this report, focus is exclusively on this default setting although an "inside or within 10 kilometre"-setting is referenced in the concluding remarks section (see further section 5).

The following brief account of the spatial analytics operations performed to determine the utilisation potentials, are divided into two different subsections according to the geometry type of the analysed datasets; point sources and rasters. The zoning feature involved in both of these sets of operations is the current district heating areas dataset (DH-A) with its 2763 unique polygons (as was outlined in Table 3 above).

As part of these spatial analyses, input, intermediate, as well as output, datasets, have been managed and handled mainly in filegeodatabases. Some data preparations have been performed inside relational databases, while the main part of data analysis and production of results have been done in Excel. Maps, and images of these, have all been rendered within the ArcGIS Pro layout architecture.

3.3.1 Point source datasets

For point sources, which included all of the 70,862 waste heat sources summarised in Table 22 in the appendix, the ArcGIS Pro "Near" geoprocessing tool (Analysis Tools), which calculates distances and determines the spatial relationship between the objects an input feature dataset relative to the closest feature in another layer or feature class, was used. In this work, a maximum search radius of 100 kilometres was applied to avoid irrelevant and time-consuming excessive calculations. Distance calculations utilised the geodesic method and resulting outputs includes attribute fields with ID´s, distances (in meter), coordinates of closest perimeter match (latitude and longitude), and angle from point source to closest perimeter match.

3.3.2 Raster datasets

For the two elaborated raster datasets (cooling from buildings in residential and service sectors, respectively), two sequential geoprocessing operations were used. In the first operation, "Extract by Mask" (Spatial Analyst Tools) was used to extracts the cells of these rasters that are located completely within current district heating area polygons (the "mask"). In the second operation, "Zonal Statistics as Table" (Spatial Analysts Tools) was used to summarise the extracted raster cell values for each of the district heating area polygons by which they had been selected, the output of which was then exported as tables for further processing.

4 Results

To present the main and key results from this work, this section is devoted only to those results which, by our used definitions, directly refer to the amounts of urban waste heat that is accessible in the EU28 (additional results are presented in appendix, see section 7.2). These results have been established according to the data, the methods, the models, and their respective updates, as has been accounted for in the above as well as in the original work, and which thereby represent the final results from the modelling and mapping of waste heat potentials in the ReUseHeat project context.

By this prioritisation, three main results dimensions will be shared in the following: the total number of unconventional urban waste heat sources in EU28 characterised by point source geometry and being located inside or within 2 kilometres of urban district heating areas (Table 19); the available waste heat in EU28 from all considered source categories which are located inside or within 2 kilometres of urban district heating areas (Table 20); and, finally, the accessible waste heat in EU28 (at practical COP of 3.0) from all considered source categories which are located inside or within 2 kilometres of urban district heating areas (Table 21).

While the total count of unconventional urban waste heat sources mapped by point source geometries (data centres, food production facilities, food retail stores, metro stations, and waste water treatment plants), was found at 70,862, as presented in appendix: Table 22 (70,771 activities in the original), only 22,756 of these are located inside or within 2 kilometres of the updated current district heating areas, as can be seen in Table 19. This number indicates an ~18% reduction in the count of point sources at this level of vicinity to such areas (27,703 in the original). The decisive explanation for this is of course the more detailed definition used here for the characterisation of current district heating areas.

Table 19 further reveals that among these point sources, food retail stores are by far the source category with most occurrences (74%), followed by waste water treatment plants (12%), whereafter the remaining source categories are found at relatively smaller shares. As in the original assessment, a couple of member states stand out with respect to total number of activities, as for example Germany (~21%), France, Poland, and the United Kingdom (all ranging in the 10% – 13% interval relative to the total count).

Table 19. Number of unconventional urban waste heat sources in EU28 by the five source categories represented by point source geometry, inside or within 2 kilometres of urban district heating areas

CC	Data Centres	Food Production	Food Retail	Metro Stations	Waste water treatment plants	Total	Share
AT	23	12	1070	48	129	1282	5.6%
BE	10	25	304	-	58	397	1.7%
BG	22	-	93	29	7	151	0.7%
CY	-	-	-	-	-	0	0.0%
CZ	22	31	549	53	315	970	4.3%
DE	190	66	3853	318	278	4705	20.7%
DK	27	20	873	9	142	1071	4.7%
EE	9	2	79	-	36	126	0.6%
EL	1	-	3	-	1	5	0.0%
ES	35	15	224	334	25	633	2.8%
FI	21	16	481	16	79	613	2.7%
FR	123	81	1488	419	332	2443	10.7%
HR	6	10	114	-	10	140	0.6%
HU	9	23	698	44	84	858	3.8%
IE	15	4	75	-	3	97	0.4%
IT	35	19	372	185	107	718	3.2%
LT	9	3	352	-	21	385	1.7%
LU	6	-	18	-	4	28	0.1%
LV	17	1	121	-	22	161	0.7%
MT	-	-	-	-	-	0	0.0%
NL	70	12	52	25	38	197	0.9%
PL	28	74	2259	27	335	2723	12.0%
PT	13	1	47	48	4	113	0.5%
RO	49	9	410	45	46	559	2.5%
SE	37	26	490	42	171	766	3.4%
SI	7	5	231	-	32	275	1.2%
SK	6	12	415	-	107	540	2.4%
UK	195	87	2162	125	231	2800	12.3%
EU28	985	554	16,833	1767	2617	22,756	100.0%
Share	4%	2%	74%	8%	12%	100%	

4.1 Available waste heat

The available waste heat at the 22,756 unique point sources located inside or within 2 kilometres of current district heating areas, plus the inside-of-such-areas sum of waste heat available from residential and service sectors buildings, expresses, if aggregated to each member state's national level and added together, the final EU28 available waste heat utilisation potential, as outlined in Table 20 below (see Table 23 in the appendix for the "total" available EU28 waste heat potential).

As can be seen in Table 20, the updated available waste heat utilisation potential has been found at very close to 800 petajoule per year (798.8) for EU28, which corresponds to approximately 222 terawatt-hours (a ~17% reduction compared to the original assessment found at 959.7 petajoule). In comparison to the "total" available potential (1849.0 petajoule, Table 23), the update utilisation potential constitutes only 43% of this total (52% in the original), which, once again, is indicative of a narrower characterisation of current district heating areas in this final assessment.

*Table 20. Available waste heat in EU28 from the seven source categories [PJ/a], inside or within 2 kilometres of urban district heating areas. Note: * available waste heat is the same value as accessible waste heat*

CC	Data Centres	Food Production	Food Retail*	Metro Stations	Residential Sector Buildings (Inside)	Service Sector Buildings (Inside)	Waste water treatment plants	Total	Share
AT	5.7	0.052	2.9	0.5	3.22	1.5	12.5	26.4	3.3%
BE	2.3	0.129	0.9	-	0.12	1.1	3.9	8.4	1.1%
BG	2.4	-	0.3	0.3	3.09	3.2	0.8	10.2	1.3%
CY	0.0	-	-	-	-	-	-	0.0	0.0%
CZ	4.9	0.013	1.8	0.4	0.30	0.9	11.6	19.9	2.5%
DE	38.1	0.299	11.9	2.7	2.45	13.8	66.5	135.7	17.0%
DK	2.5	0.289	2.5	0.1	0.45	1.0	8.9	15.7	2.0%
EE	0.7	0.012	0.2	-	0.27	0.7	2.0	3.8	0.5%
EL	0.3	-	0.0	-	0.40	0.7	0.0	1.4	0.2%
ES	11.2	0.043	0.9	4.1	15.89	27.2	10.3	69.5	8.7%
FI	6.8	0.215	1.2	0.1	0.09	1.0	7.4	16.8	2.1%
FR	30.0	0.319	4.8	4.4	7.06	28.8	49.7	125.2	15.7%
HR	1.2	0.015	0.4	-	0.02	1.5	2.4	5.6	0.7%
HU	3.7	0.099	2.3	0.5	0.95	2.0	8.8	18.4	2.3%
IE	1.6	0.008	0.2	-	0.01	0.2	3.8	5.9	0.7%
IT	12.8	0.026	1.3	2.4	28.21	34.8	21.0	100.6	12.6%
LT	0.7	0.022	1.0	-	0.09	0.2	1.7	3.7	0.5%
LU	0.2	-	0.1	-	0.01	0.0	0.3	0.7	0.1%
LV	0.6	0.003	0.3	-	0.01	0.1	0.5	1.6	0.2%
MT	0.0	-	-	-	-	-	-	0.0	0.0%
NL	6.4	0.112	0.2	0.2	0.08	1.3	8.0	16.3	2.0%
PL	11.1	0.266	6.2	0.2	1.66	3.8	30.6	53.9	6.7%
PT	2.1	0.000	0.2	0.7	0.13	1.8	1.4	6.3	0.8%
RO	3.9	0.015	1.5	0.5	2.54	4.6	8.1	21.1	2.6%
SE	8.4	0.110	1.3	0.3	1.42	2.3	11.3	25.2	3.2%
SI	1.1	0.006	0.7	-	0.01	0.8	1.1	3.7	0.5%
SK	0.9	0.012	1.3	-	0.01	0.3	3.7	6.2	0.8%
UK	19.9	0.414	5.5	1.1	0.50	13.9	55.4	96.6	12.1%
EU28	179.6	2.479	49.9	18.5	69.0	147.6	331.8	798.8	100.0%
Share	22%	0.3%	6%	2%	9%	18%	42%	100%	

Despite only having the second highest count of facilities, the relative contribution from waste water treatment plants (42%) constitutes by far the largest volume at the default distance constraint setting, followed by data centres (22%). Notably, by model update, the absolute volume recorded for data centres (179.6 petajoule), despite being only marginally lower than in the original (180.4 petajoule), results in a relative share that has increased by three percent (19% in the original). Food retail stores, while constituting 74% of the total count, represent only 6% of the available waste heat potential, which is an indication of the relatively lower waste heat volumes per facility in this sector.

Among the member states, Germany, again, hosts the largest annual volumes at 17% of the total (135.7 petajoules, or ~38 terawatt-hours), followed by France (16%, 125.2 petajoules), and, notably, Italy (13%, 100.6 petajoules). An EU28 member state average value for the "total" available potential is conceivable at 66 petajoule per year and country (66 also in the original). This can be compared to a corresponding available utilisation potential average found at 29 petajoule per year and country (34 in the original).

4.2 Accessible waste heat

If all the available waste heat here mapped and modelled would feed compressor heat pumps operating with average practical COP´s of 3.0, the accessible utilisation potential in the EU28, thus under the default spatial constraint, and as detailed in Table 21, amounts to 1173.3 petajoule per year, or ~326 terawatt-hours (1409.7 petajoule in the original, and hence, in analogy, also here corresponding to a ~17% reduction). If spatially unconstrained, as presented in appendix Table 24, the "total" accessible waste heat potential in the EU28 skyrockets up to some 2700 petajoule (~750 terawatt-hours), but this number has little practical significance since it reflects a rather illusory magnitude.

*Table 21. Accessible waste heat in EU28 from the seven source categories [PJ/a], inside or within 2 kilometres of urban district heating areas at a practical COP of 3.0. Note: * accessible waste heat is the same value as available waste heat*

CC	Data Centres	Food Production	Food Retail*	Metro Stations	Residential Sector Buildings (Inside)	Service Sector Buildings (Inside)	Waste water treatment plants	Total	Share
AT	8.5	0.078	2.9	0.7	4.84	2.3	18.8	38.2	3.3%
BE	3.4	0.194	0.9	-	0.18	1.7	5.8	12.2	1.0%
BG	3.6	-	0.3	0.4	4.63	4.8	1.3	15.1	1.3%
CY	0.0	-	-	-	-	-	-	0.0	0.0%
CZ	7.3	0.019	1.8	0.6	0.44	1.4	17.4	29.0	2.5%
DE	57.1	0.449	11.9	4.0	3.67	20.7	99.8	197.7	16.8%
DK	3.8	0.433	2.5	0.1	0.67	1.5	13.4	22.3	1.9%
EE	1.0	0.018	0.2	-	0.41	1.0	3.0	5.7	0.5%
EL	0.5	-	0.0	-	0.59	1.0	0.0	2.1	0.2%
ES	16.7	0.064	0.9	6.2	23.83	40.8	15.4	103.9	8.9%
FI	10.2	0.322	1.2	0.2	0.14	1.4	11.1	24.6	2.1%
FR	45.0	0.479	4.8	6.6	10.59	43.3	74.5	185.3	15.8%
HR	1.8	0.023	0.4	-	0.02	2.2	3.6	8.2	0.7%
HU	5.6	0.149	2.3	0.7	1.43	3.1	13.2	26.4	2.3%
IE	2.5	0.012	0.2	-	0.01	0.3	5.8	8.8	0.7%
IT	19.1	0.039	1.3	3.7	42.32	52.3	31.6	150.2	12.8%
LT	1.1	0.033	1.0	-	0.14	0.2	2.5	5.0	0.4%
LU	0.3	-	0.1	-	0.01	0.1	0.5	1.0	0.1%
LV	0.9	0.005	0.3	-	0.01	0.2	0.8	2.2	0.2%
MT	0.0	-	-	-	-	-	-	0.0	0.0%
NL	9.5	0.168	0.2	0.3	0.12	2.0	12.0	24.4	2.1%
PL	16.7	0.399	6.2	0.3	2.50	5.7	45.9	77.7	6.6%
PT	3.2	0.001	0.2	1.0	0.20	2.7	2.0	9.3	0.8%
RO	5.9	0.022	1.5	0.7	3.81	6.9	12.1	31.0	2.6%
SE	12.7	0.165	1.3	0.5	2.13	3.5	16.9	37.2	3.2%
SI	1.6	0.008	0.7	-	0.02	1.2	1.7	5.1	0.4%
SK	1.4	0.018	1.3	-	0.01	0.4	5.5	8.7	0.7%
UK	29.8	0.621	5.5	1.6	0.75	20.8	83.1	142.2	12.1%
EU28	269.4	3.718	49.9	27.7	103.5	221.4	497.7	1173.3	100.0%
Share	23%	0.3%	4%	2%	9%	19%	42%	100%	

In terms of member states, the distribution is similar to that for available waste heat, where the five largest includes Germany (~17%), France (~16%~), Italy (13%), United Kingdom (12%), and Spain (~9%). The accessible annual waste heat potential from waste water treatment plants, also here representing the largest annual source category volume, is found at approximately 500 petajoule per year (497.7 petajoule, or ~138 terawatt-hours), which is indicative of a 20% reduction compared to the original (~625 petajoule).

When reflecting however on the relative increase of the available waste heat potential from waste water treatment plants, as presented in appendix Table 25 for a referential "inside-or-within-10-kilometres" spatial constraint setting, compared to the "inside-or-within-2-kilometres" default setting, it is clear that transmission distances are particularly important for this source category. The relative increase reaches 65% (546.0 petajoule available at 10 kilometres and 331.8 petajoule available at 2 kilometres, as shown in Table 20), and given their analogous relationship in this particular sense, this circumstance is applicable for available as well as for accessible waste heat potentials regarding this source category.

Due to the second aspect of the metro station model update, accounted for in subsection 3.2.2 above, the accessible waste heat potential from metro stations is lower here in the update compared to the original work. Whereas this potential previously was assessed at 48.6 petajoule (~14 terawatt-hours), it has been reduced here to 27.7 petajoule (~7.7 terawatt-hours).

Noteworthy, at the default spatial constraint setting, accessible waste heat from data centres have maintained principally the same volumes here (269.4 petajoule, or ~75 terawatt-hours) as in the original (270.6 petajoule), which may be explained by a countereffect; while using a narrower definition of current district heating areas, the data centre model update increased the total count from 1269 to 1360. Data centres, unlike waste water treatment plants, moreover, seem regularly to be located deep inside urban areas.

In summary, the complete result from this work is presented in the form of staple bars, by annual energy unit, and by logarithmic scale, in Figure 14. This graph presents the results coherently for the two waste heat dimensions (available (Q_L) and accessible (Q_H)), the two spatial settings ("total" (All) and "2km" (default spatial constraint of being located inside or within 2 kilometres of current district heating areas)), and, as well, for the two different versions of this work (the original work (D1.4) and this update (D1.9)). Black staples represent the originally conceived recovery potentials stated in the project proposal.

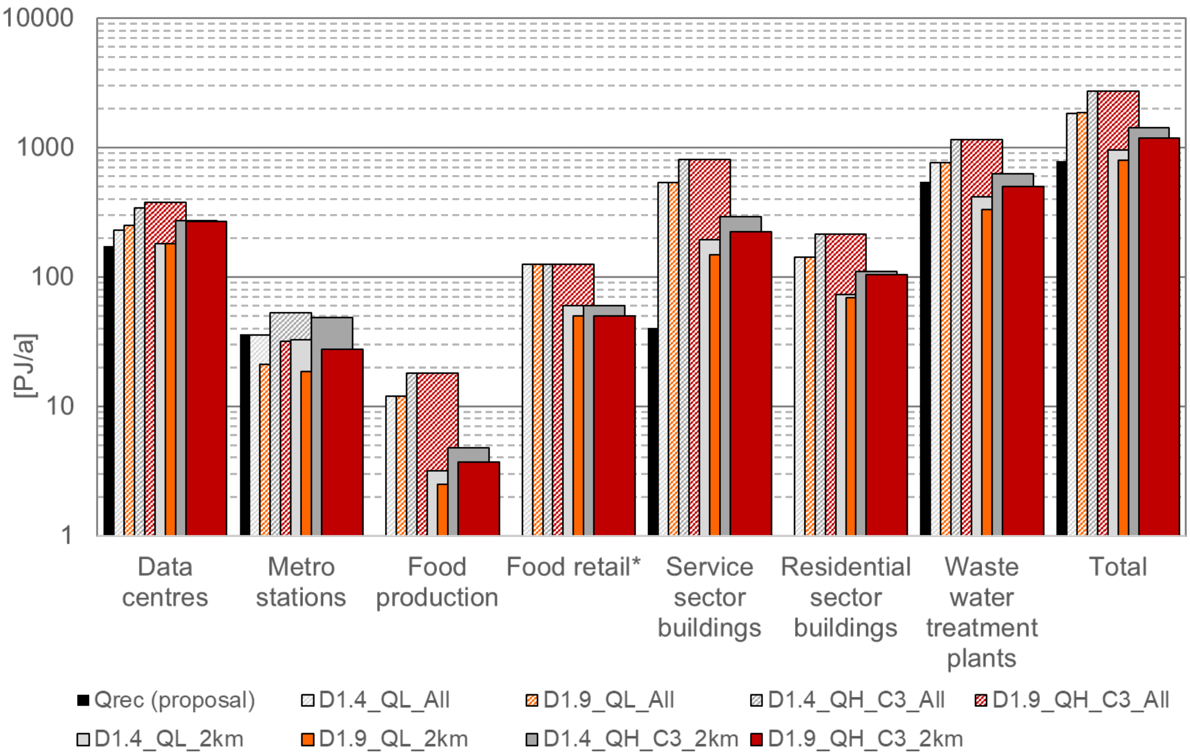

Figure 14. Summary update overview of modelled available (Q_L) and accessible (Q_H) waste heat volumes inside or within 2 kilometres of urban district heating areas (2km) vs. volumes unrestricted by local conditions (All) within the EU28, by source category, with comparison to recoverable waste heat volumes (Q_{rec}), as anticipated in the project proposal, and with comparison to the original work (D1.4).

5 Concluding remarks

To conclude, this report has presented the final and updated work performed in Task T1.2 of the ReUseHeat project, which objective has been to assess the accessible EU28 urban waste heat recovery potential from seven unconventional urban waste heat sources. These seven source categories are, in alphabetic order, data centres, food production facilities, food retail stores, metro stations, cooling of residential sector buildings, cooling of service sector buildings, and waste water treatment plants.

Being an update, and where applicable, the presentation has been made with references to the original work (the revised version of the D1.4 deliverable report titled *Accessible urban waste heat*), and by keeping to the main methods and concepts developed and used in the original. Hereby, the originally conceived and introduced concepts of *available waste heat* and *accessible waste heat* have been used to denote and emphasise that a resource, a physical asset, is something quite different from a commodity, a marketed product. In this context, this translates into the resource of low-grade residual heat generated in the above-mentioned unconventional sources and the commodity of heat distributed in district heating systems and sold to its connected customers.

In addition, the presentation involves and enhances, relative to the original work, also a geographical distinction which is made with reference to both available and accessible waste heat potentials. Unconstrained spatial contexts, on the one hand, are referred to as "total potentials", while, on the other hand, spatial delineation by reference to current district heating areas, in particular at a default setting of "inside-or-within-2-kilometres" of such district heating areas, are referred to as "utilisation potentials". The rationale for this distinction is that heat distribution infrastructures need to be in place to facilitate large-scale recovery and reuse of these assets, hence, the label "utilisation potential".

The presentation further includes references to monitoring data from five project demo-sites: Berlin (DE); Brunswick (DE); Bucharest (RO); Madrid (ES); and Nice (FR)), where installations concerning four of the considered source categories (metro stations, data centres, cooling of service sector buildings, and waste water treatment plants) have been developed and brought into operation (in selected cases). The presentation further includes responses made to an online project questionnaire on existing waste heat initiatives.

Model updates adopted in this work include that for source categories data centres, where new input data has been elaborated, and metro stations, for which developments regarding two model aspects have been made (among other the introduction of a traffic intensity parameter). A third element among the model updates refers to the use of a more refined and detailed dataset for the geographical representation of current district heating areas, a publicly available dataset developed in the parallel EU Horizon 2020 project sEEnergies.

As for the final result, a total of 70,862 unique point source activities constitutes the total population of study objects (70,771 in the original), excluding residential and service sector buildings which were characterised by raster representation. The total available waste heat potential is assessed at some 1849 petajoule per year (~514 terawatt-hours), compared to the original 1842 petajoule per year. At the default spatial constraint setting, the final available waste heat potential is estimated at ~800 petajoule per year (~222 terawatt-hours) from a thus reduced subset of 22,756 unique point-source locations (960 petajoule per year from 27,703 unique facilities in the original), which here corresponds to a final accessible EU28 waste heat utilisation potential anticipated at 1173 petajoule (~326 terawatt-hours) annually (previous assessment at 1410 petajoule annually).

As a reference outlook, considering instead a spatial constraint setting of being "inside-or-within-10-kilometres" of current district heating areas, which may be seen as an equally realistic heat transmission distance as that in the default setting, reveals an available EU28 waste heat utilisation potential from unconventional sources in the order of one exajoule per year (1085 petajoule, or some ~300 terawatt-hours), a perhaps easy number to remember from these investigations. For improved dissemination and exploitation of project results, finally, a new web map; *the European Waste Heat Map*, has been made available where point source data from this work may be viewed and shared.

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7 Appendix

7.1 The European Waste Heat Map

The web map developed in association with this work, the European Waste Heat Map, is intended as a comprehensive and publicly available European web map and data source on waste heat activities that could become useful for the decarbonisation and green transition of the European heat sector. At current, the web map is still in a draft work-in-progress mode (date as of report submission) and includes initially only datasets that are related to this update. In the future, we hope that the web map may be populated with datasets created in other projects and contexts as well, and, perhaps, eventually, it may grow wings and fly by its own.

As illustrated in the screenshot presented in Figure 15, the key layer currently available is that labelled "D1.9 Waste heat point sources", which includes, with the exclusion of the 1360 data centres, all waste heat sources characterised by point source geometries which have been part of this update. Regarding data centres, due to sharing restrictions, this dataset is included as a separate layer for visualisation only. Noteworthy, two data sets from the EU Horizon 2020 project sEEnergies, the D5.1 industry dataset and the D5.1 District Heating Areas dataset (the zoning dataset used for the spatial analyses performed here) are also included in the new web map.

Using the web map is intended to be quite straight forward. By accepting the terms of use at the welcome screen, you will directly arrive at the web map, where you can open a table of contents and select the layer you want to view. Where applicable, layers are intended to be, or become, downloadable under the Creative Commons CC BY 4.0 licence.

Once again, we invite you to visit the new web map by following this link:

https://tinyurl.com/2wvh7ud7

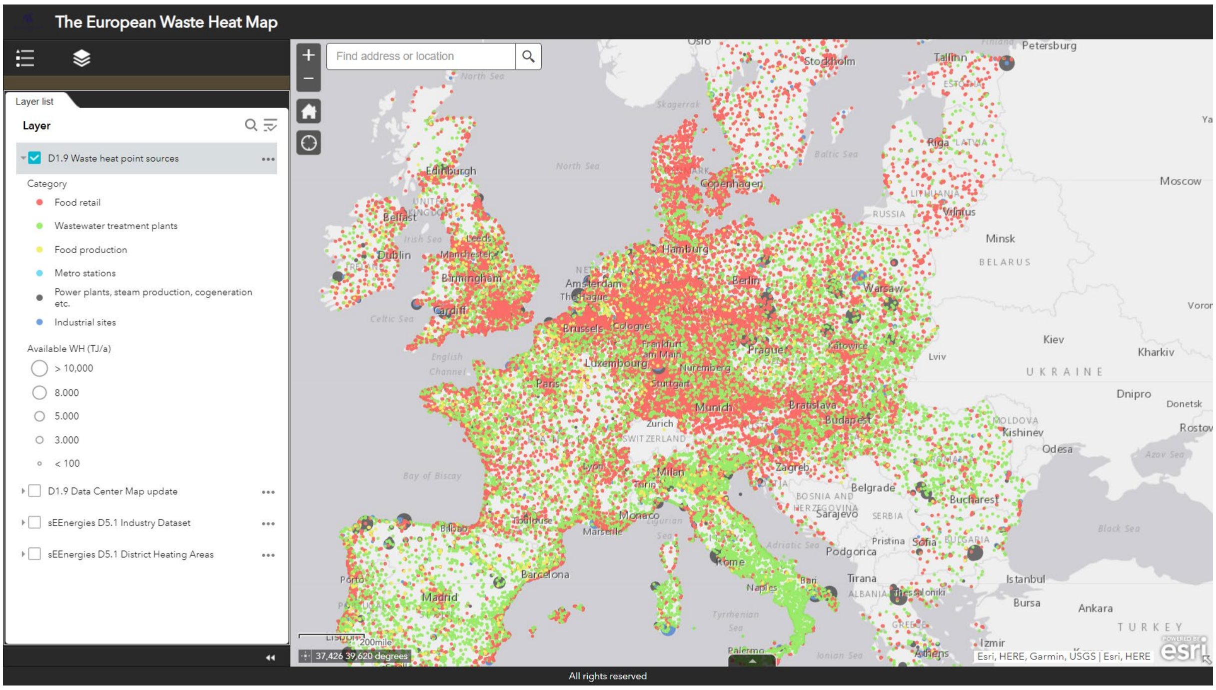

Figure 15. Screenshot from the new European Waste Heat Map with the layer "D1.9 Waste heat point sources" activated.

7.2 Additional result tables

Table 22. Number of unconventional urban waste heat sources in EU28 by the five source categories represented by point source geometry

CC	Data Centres	Food Production	Food Retail	Metro Stations	Waste water treatment plants	Total	Share
AT	23	19	2076	48	634	2800	4.0%
BE	32	111	1396	47	402	1988	2.8%
BG	25	5	151	29	104	314	0.4%
CY	13	-	26	-	15	54	0.1%
CZ	24	52	627	53	600	1356	1.9%
DE	222	321	12541	318	4244	17646	24.9%
DK	31	31	1450	9	343	1864	2.6%
EE	10	4	148	-	57	219	0.3%
EL	14	6	156	37	159	372	0.5%
ES	64	276	1936	407	2020	4703	6.6%
FI	22	24	776	17	163	1002	1.4%
FR	157	493	4539	441	3610	9240	13.0%
HR	7	16	268	-	81	372	0.5%
HU	9	36	1244	44	747	2080	2.9%
IE	24	66	367	-	167	624	0.9%
IT	70	184	1554	214	3953	5975	8.4%
LT	12	9	603	-	75	699	1.0%
LU	15	1	64	-	33	113	0.2%
LV	17	1	190	-	89	297	0.4%
MT	8	-	9	-	4	21	0.0%
NL	110	147	343	25	337	962	1.4%
PL	32	166	3094	27	1665	4984	7.0%
PT	26	42	744	48	467	1327	1.9%
RO	51	27	660	45	556	1339	1.9%
SE	50	39	886	45	432	1452	2.0%
SI	8	8	419	-	91	526	0.7%
SK	14	13	634	-	263	924	1.3%
UK	270	390	4931	140	1878	7609	10.7%
EU28	1360	2487	41,832	1994	23,189	70,862	100.0%
Share	2%	4%	59%	3%	33%	100%	

*Table 23. Available waste heat in EU28 from the seven source categories [PJ/a]. Note: * available waste heat is the same value as accessible waste heat*

CC	Data Centres	Food Production	Food Retail*	Metro Stations	Residential Sector Buildings	Service Sector Buildings	Waste water treatment plants	Total	Share
AT	5.7	0.079	5.5	0.5	3.22	2.6	20.7	38.2	2.1%
BE	7.3	0.770	3.8	0.5	0.85	7.4	11.6	32.4	1.7%
BG	2.7	0.003	0.5	0.3	3.72	5.7	7.7	20.7	1.1%
CY	0.4	-	0.1	-	0.18	4.1	1.1	5.9	0.3%
CZ	5.3	0.019	2.0	0.4	0.34	1.5	14.1	23.8	1.3%
DE	44.5	1.674	38.9	2.7	2.54	38.7	165.8	294.8	15.9%
DK	2.9	0.502	4.0	0.1	0.45	1.7	11.2	20.9	1.1%
EE	0.8	0.024	0.3	-	0.28	1.4	2.3	5.1	0.3%
EL	4.4	0.002	0.6	0.5	15.87	79.0	11.2	111.5	6.0%
ES	20.4	0.615	7.6	4.8	36.32	116.8	64.2	250.7	13.6%
FI	7.1	0.285	1.9	0.1	0.10	1.9	12.0	23.4	1.3%
FR	38.3	1.804	14.8	4.7	7.09	51.0	90.5	208.2	11.3%
HR	1.4	0.023	1.0	-	0.02	2.4	4.0	8.8	0.5%
HU	3.7	0.114	3.8	0.5	0.99	3.3	13.5	25.8	1.4%
IE	2.6	1.021	1.1	-	0.02	0.5	6.6	11.9	0.6%
IT	25.5	0.290	5.0	2.9	62.55	146.4	81.0	323.7	17.5%
LT	1.0	0.067	1.7	-	0.17	0.4	4.4	7.7	0.4%
LU	0.6	0.010	0.2	-	0.02	0.2	1.0	1.9	0.1%
LV	0.6	0.003	0.5	-	0.01	0.2	2.2	3.5	0.2%
MT	0.2	-	0.0	-	0.00	2.9	0.4	3.6	0.2%
NL	10.0	1.194	1.0	0.2	0.09	4.7	26.8	44.0	2.4%
PL	12.7	0.561	8.2	0.2	1.96	7.7	54.5	85.9	4.6%
PT	4.3	0.065	2.8	0.7	0.15	9.3	11.0	28.4	1.5%
RO	4.1	0.057	2.4	0.5	2.72	6.9	17.5	34.1	1.8%
SE	11.4	0.174	2.2	0.3	1.67	5.0	16.5	37.3	2.0%
SI	1.2	0.007	1.2	-	0.01	2.1	2.2	6.7	0.4%
SK	2.2	0.013	1.7	-	0.01	0.6	5.5	10.0	0.5%
UK	27.5	2.559	13.0	1.2	0.75	31.8	103.3	180.1	9.7%
EU28	248.9	11.933	125.7	21.0	142.1	536.2	763.0	1849.0	100.0%
Share	13%	0.6%	7%	1.1%	8%	29%	41%	100%	

*Table 24. Accessible waste heat in EU28 from the seven source categories [PJ/a] at a practical COP of 3.0. Note: * accessible waste heat is the same value as available waste heat*

CC	Data Centres	Food Production	Food Retail*	Metro Stations	Residential Sector Buildings	Service Sector Buildings	Waste water treatment plants	Total	Share
AT	8.5	0.119	5.5	0.7	4.84	3.9	31.1	54.5	2.0%
BE	11.0	1.155	3.8	0.7	1.28	11.1	17.4	46.6	1.7%
BG	4.1	0.004	0.5	0.4	5.57	8.6	11.6	30.8	1.1%
CY	0.6	-	0.1	-	0.27	6.2	1.6	8.7	0.3%
CZ	8.0	0.029	2.0	0.6	0.51	2.2	21.2	34.6	1.3%
DE	66.7	2.511	38.9	4.0	3.81	58.1	248.8	422.8	15.6%
DK	4.3	0.752	4.0	0.1	0.67	2.6	16.9	29.3	1.1%
EE	1.1	0.035	0.3	-	0.43	2.1	3.4	7.5	0.3%
EL	6.6	0.004	0.6	0.8	23.81	118.5	16.8	167.0	6.2%
ES	30.6	0.922	7.6	7.2	54.47	175.1	96.3	372.2	13.7%
FI	10.7	0.427	1.9	0.2	0.15	2.8	17.9	34.1	1.3%
FR	57.4	2.706	14.8	7.0	10.64	76.6	135.7	304.9	11.2%
HR	2.1	0.035	1.0	-	0.02	3.5	6.1	12.8	0.5%
HU	5.6	0.171	3.8	0.7	1.48	4.9	20.2	36.9	1.4%
IE	3.9	1.532	1.1	-	0.03	0.7	10.0	17.3	0.6%
IT	38.3	0.435	5.0	4.3	93.83	219.6	121.5	483.0	17.8%
LT	1.4	0.101	1.7	-	0.26	0.7	6.7	10.8	0.4%
LU	0.9	0.015	0.2	-	0.04	0.3	1.5	2.8	0.1%
LV	0.9	0.005	0.5	-	0.02	0.3	3.3	5.0	0.2%
MT	0.3	-	0.0	-	0.01	4.4	0.6	5.4	0.2%
NL	15.0	1.790	1.0	0.3	0.14	7.0	40.2	65.5	2.4%
PL	19.1	0.841	8.2	0.3	2.94	11.5	81.7	124.7	4.6%
PT	6.4	0.098	2.8	1.0	0.22	14.0	16.6	41.2	1.5%
RO	6.1	0.085	2.4	0.7	4.08	10.3	26.3	50.0	1.8%
SE	17.1	0.261	2.2	0.5	2.51	7.5	24.7	54.8	2.0%
SI	1.8	0.010	1.2	-	0.02	3.1	3.3	9.5	0.3%
SK	3.3	0.019	1.7	-	0.02	1.0	8.2	14.2	0.5%
UK	41.3	3.839	13.0	1.8	1.13	47.8	155.0	263.7	9.7%
EU28	373.4	17.900	125.7	31.6	213.2	804.3	1144.5	2710.6	100.0%
Share	14%	0.7%	5%	1.2%	8%	30%	42%	100%	

*Table 25. Available waste heat in EU28 from the seven source categories [PJ/a], inside or within 10 kilometres of urban district heating areas. Note: * available waste heat is the same value as accessible waste heat*

CC	Data Centres	Food Production	Food Retail*	Metro Stations	Residential Sector Buildings (Inside)	Service Sector Buildings (Inside)	Waste water treatment plants	Total	Share
AT	5.7	0.070	4.8	0.5	3.22	1.5	19.5	35.3	3.3%
BE	3.9	0.394	2.1	-	0.12	1.1	6.2	13.8	1.3%
BG	2.4	0.001	0.4	0.3	3.09	3.2	5.5	14.8	1.4%
CY	0.4	-	0.1	-	-	-	1.1	1.6	0.1%
CZ	5.3	0.017	2.0	0.4	0.30	0.9	14.0	22.9	2.1%
DE	41.9	0.553	20.2	2.7	2.45	13.8	103.2	184.8	17.0%
DK	2.9	0.502	3.7	0.1	0.45	1.0	10.7	19.3	1.8%
EE	0.8	0.018	0.2	-	0.27	0.7	2.1	4.0	0.4%
EL	3.5	0.002	0.4	0.5	0.40	0.7	8.9	14.4	1.3%
ES	18.2	0.295	4.8	4.4	15.89	27.2	43.3	114.0	10.5%
FI	6.8	0.255	1.5	0.1	0.09	1.0	11.4	21.0	1.9%
FR	34.9	0.542	7.1	4.4	7.06	28.8	61.7	144.5	13.3%
HR	1.2	0.015	0.6	-	0.02	1.5	3.0	6.3	0.6%
HU	3.7	0.105	2.8	0.5	0.95	2.0	11.3	21.4	2.0%
IE	2.6	0.194	0.6	-	0.01	0.2	5.0	8.6	0.8%
IT	17.9	0.132	2.6	2.9	28.21	34.8	52.7	139.2	12.8%
LT	1.0	0.025	1.3	-	0.09	0.2	4.1	6.6	0.6%
LU	0.4	-	0.1	-	0.01	0.0	0.7	1.3	0.1%
LV	0.6	0.003	0.4	-	0.01	0.1	2.0	3.2	0.3%
MT	0.2	-	0.0	-	-	-	0.4	0.7	0.1%
NL	7.4	0.300	0.3	0.2	0.08	1.3	13.0	22.6	2.1%
PL	12.3	0.404	7.3	0.2	1.66	3.8	50.0	75.7	7.0%
PT	4.3	0.051	2.2	0.7	0.13	1.8	8.6	17.8	1.6%
RO	4.1	0.030	1.7	0.5	2.54	4.6	12.8	26.2	2.4%
SE	10.7	0.148	1.7	0.3	1.42	2.3	14.9	31.5	2.9%
SI	1.2	0.006	0.9	-	0.01	0.8	1.9	4.9	0.4%
SK	2.2	0.013	1.6	-	0.01	0.3	5.4	9.6	0.9%
UK	23.0	0.844	7.4	1.1	0.50	13.9	72.7	119.4	11.0%
EU28	219.4	4.919	78.7	19.8	69.0	147.6	546.0	1085.4	100.0 %
Share	20%	0.5%	7%	2%	6%	14%	50%	100%	

ReUseHeat