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Revision note:

This report constitutes the revised version of the original D1.4 deliverable report in the ReUseHeat project. The revisions performed are in response to the evaluation items expressed in the review report from the first project review (RV1). Hereby, to this revised version has been added three additional unconventional heat sources; rejected heat from refrigeration processes in the food production sector, rejected heat from refrigeration processes in the food retail sector, as well as rejected heat from the cooling of buildings in the residential sector.

Due to these additions, corresponding changes have been made in several of the report sections. **Changes made within a section is indicated by one asterisk (*)** in the section header. To account for the addition of the three new sources, three new main sections have been introduced into the Table of Contents; Food production refrigeration, Food retail refrigeration, and Cooling of residential sector buildings. **New sections are indicated by two asterisks (**)** in the section header.

Since none of the four project demo sites represent activities in any of the three added sectors, no changes have been made with reference to the demo-sites section. After the time of writing the original version of this report, November 2018, two of the then planned demo sites have been replaced (Metro system of Bucharest and the hospital in Madrid). None of these changes are reflected in this revised version of D1.4, since they will be part of the general update of D1.4, which is to be presented in the D1.9 report, scheduled for March 2021.

For the same reason, work performed post November 2018 to develop and improve the models presented in the original work, concerning for example the excess heat potentials from data centres and metro systems in Europe, as well as the delineation of representative district heating areas, is not reflected in this revised version, but will be presented in the D1.9 deliverable.

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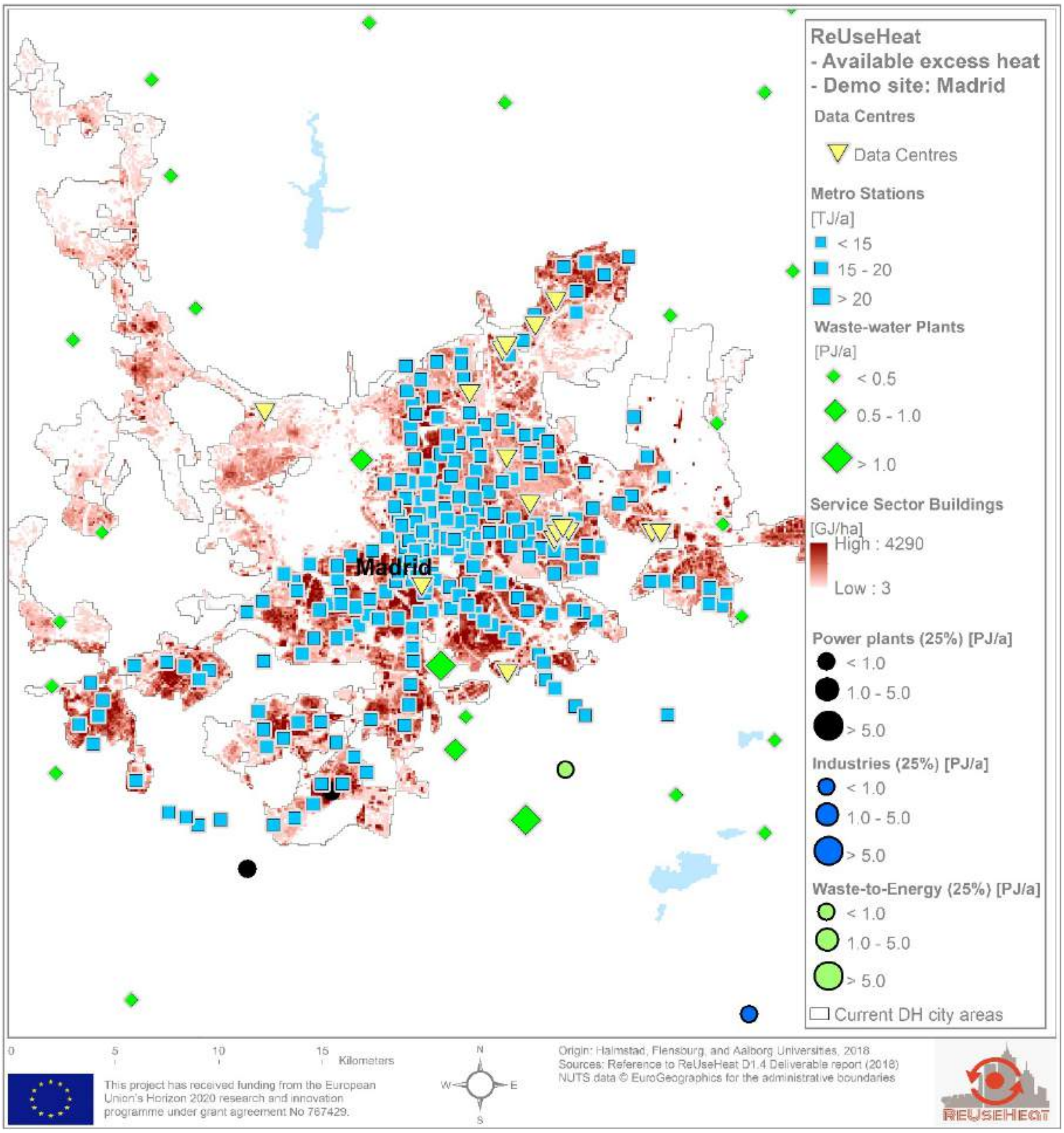

Figure 1. Mapping of available urban excess heat from four unconventional and three conventional sources in the city area of Madrid, one of four project demonstration sites.

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Summary*

This report presents the revised work performed in Task T1.2 of the ReUseHeat project to assess the accessible EU28 urban excess heat recovery potential from seven unconventional excess 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 presents in overview and detail the concepts, data, basic premises, and methods, used to produce the results from this work. In all, excess heat potentials are modelled and spatially mapped for a total of some 70,800 unique activities, but by application of two new concepts: available excess heat and accessible excess heat, by which total potentials are distinguished from practical utilisation potentials, a significantly reduced count of some 27,700 unique facilities represent the final cut. Common for these facilities are that they all are located inside or within 2 kilometres of urban district heating areas. For the total count of activities, the full available excess heat potential is assessed at some 1.84 EJ per year. At the restrained conditions, thus representing a conservative estimate, the final available excess heat potential from the seven unconventional sources is estimated at 0.96 EJ per year, which here corresponds to a final accessible excess heat potential anticipated at 1.41 EJ annually.

Acknowledgements*

The potential assessments presented in this report has been made possible partly by use of datasets and approaches developed in the Heat Roadmap Europe (HRE) project, which is hereby gratefully acknowledged. The public web map application developed within this project, PETA 4.3 (the Pan-European Thermal Atlas, version 4.3), has further provided valuable opportunity for the dissemination of outputs generated in the ReUseHeat project, an opportunity for which we are equally grateful.

For two of the seven investigated unconventional urban excess heat sources in this study, those of rejected heat from cooling of residential and service sector buildings, this project has relied partly on data generated within the HotMaps project. Despite that the project operates under an open data regime, by which the used datasets are publicly available, we still want to express our gratitude for being able to access and use this information in the context of this study.

During the course of this work, several comments have also been received from project partners and associates, especially so during discussions at two general assembly meetings held in 2018 (Bucharest in March and Brunswick in October). We would hereby like to acknowledge our gratefulness for the valuable inputs received at these occasions.

For their kind sharing of input data and expertise, we would also like to express our thankfulness and gratitude to Engineer Anders Svensson, formerly at the district heating operator in the city of Lund, Sweden (Kraftringen AB), and to Dr. Michael Cimbritz at Lund University, Sweden.

1 Introduction*

The *Recovery of Urban Excess Heat* (ReUseHeat) project [1], is a 48-month European 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 general objective of the project is to demonstrate, at TRL8 (Technology Readiness Level), first of their kind advanced, modular and replicable systems enabling the recovery and reuse of waste heat (a.k.a. excess heat) available at the urban level. The project further explicitly builds on previous knowledge from other EU funded projects (notably CELSIUS [2], Stratego [3] and Heat Roadmap Europe [4]) and intends to overcome both technical and non-technical barriers towards the unlocking of urban waste heat recovery investments across Europe.

To meet these objectives, the main focus of the ReUseHeat project is directed, on the one hand, to the study of non-technical dimensions that may have impact on the feasibility of excess heat recoveries in Europe, such as e.g. legal, fiscal, contractual, and business model aspects. On the other hand, dedicated technical focus is also devoted to four demonstration sites (Brunswick (DE), Bucharest (RO), Madrid (ES), and Nice (FR)), where four project considered unconventional urban excess heat sources are to become operational and monitored during the project lifetime, one at each location.

While these two objectives are central for the project, the work presented in this report serves a more supportive and complementary function, since its main purport is to facilitate an understanding by which to assess the scalability and replicability of the four demo-site case technologies. This work, therefore, is devoted to the development of spatial and statistical models whereby to estimate the geographical distribution and magnitude of such urban excess heat sources for the entirety of the EU28 and its member states. By developing such models, the means and measures, as well as general references, for such an understanding is made possible. The main purpose of this report is thus to provide an indication as of the full EU28 excess heat recovery potential from the considered urban excess heat sources.

The report is principally structured in analogy with the studied urban excess heat sources, see sections: 3 Data centres, 4 Metro stations, 5 Food production, 6 Food retail, 7 Service sector buildings, 8 Residential sector buildings, and 9 Waste water treatment plants, but begins with a general overview presentation of the various models, approaches, and assumptions used for the generation of study results (section 2 Methods overview). Detailed accounts of source specific methods, data, and results for each of the studied categories are given under each corresponding topic. In section 10 Demo-sites, the findings for each of the four demo-sites are reported along with a summary, while sections: 11 Main results; 12 Discussion; and 13 Conclusions, present and discuss the overall findings of the study together with some concluding remarks. To maintain the main body of report text as readable as possible, larger tables and auxiliary material has been placed in a separate Appendix (see section 15).

1.1 General objective*

The main aim of this report is to provide a thorough account and description of the work carried out under Task 1.2 (T1.2) in Work Package 1 (WP1) of the ReUseHeat project. In analogy with the task description in the grant agreement (GA) [5], see also appendix 15.1, the overall objective of this work is to quantify the accessible urban excess heat potential at the urban level for all EU28 member states with regards to seven unconventional excess heat sources, and, likewise, for the four project demo-sites, to assess also the accessible urban excess heat potential from conventional sources. In this context, the seven considered unconventional urban excess heat sources are: data centres; metro stations; food production facilities; food retail stores; service sector buildings; residential sector buildings; and waste water treatment plants (a.k.a. sewages). For the demo-sites, the three conventional excess heat sources considered are: power plants; industrial facilities (energy-intensive); and Waste-to-Energy plants.

As a general reference for the urban excess heat potentials to be estimated here, the pre-conceived annual volumes of recoverable urban excess heat (Q_{rec}) , as stipulated in the GA (at page 31, Part B), is given in Table 1. It should be noted that no further distinction is made in the GA whether the term "recoverable" excess heat refers to that heat that would be available at the sources themselves, or that heat – here termed "accessible", for further definitions, see sections 2.4.2 and 2.4.3 below – that would be accessible for large-scale utilisation given the presence of appropriate means for such recoveries.

Table 1. Annual volumes of recoverable urban excess heat from the considered unconventional urban excess heat sources in EU28, as anticipated in the project grant agreement (p. 31, Part B) [5]

Source	**Q_{rec} [PJ/a]**
Data centres	173
Metro stations	36
Food production facilities	Not specified
Food retail stores	Not specified
Service sector buildings	40[a]
Residential sector buildings	Not specified
Waste water treatment plants	540
Total	**789**

[a] Note that this volume refers to hospitals only since the Madrid demo-site considers such a case. In the T1.2 potential assessment the complete service sector is considered, of which hospitals are merely a part.

This notion is in fact one of several key considerations in this work. As is further elaborated in section 2, a distinction is made uniformly between excess heat *available* at any given source, and that which is *accessible*. This distinction relies principally on two different dimensions, first, that of considered excess heat sources all being so-called *low-temperature* sources, which for their practical utilisation depend on heat pump applications, and, second, that of their spatial correlation to heat distribution infrastructures, without which no large-scale recovery and utilisation in the form of heat is conceivable.

With these considerations kept in mind, it may be concluded from Table 1 that some 790 PJ per year constitute the anticipated EU28 benchmark potential onto which the modelling in this work will be related and compared. In itself, this is quite a significant magnitude of annual energy, especially when remembering that the numbers for the service sector buildings (40 PJ/a) refers to hospitals only (in correspondence with the Madrid demo-site object). However, by subsequent steering committee decision (2018-07-02), the scope of this source category has been extended to cover the entire service sector (of which hospitals merely are a part). For this reason, it is likely that the anticipated total volume in Table 1 may constitute a slight underestimate compared to the potentials that are to be assessed here.

1.2 Background and context

The current day interest and awareness within the European community concerning energy efficiency as a key measure to obtain reduced primary energy demands and lowered greenhouse gas emissions, a few among many recognised benefits, may perhaps be stronger and clearer now than ever before. Remarkably so, this awareness has, during only the last decade, come to include more pronouncedly also the systemic perspective, i.e. an understanding of the full significance of viewing the energy system in its entirety to identify its inherent opportunities for synergies and operational integrations [6-10]. Excess heat recovery, initially so conceived essentially from energy and industry sector activities, was a deliberate objective formulated in the 2012 energy efficiency directive [11], and was also a recurring theme in the 2016 strategy on heating and cooling of the European Commission [12-14].

In this context, the objectives of the ReUseHeat project, i.e. to map accessible urban excess heat from low-temperature sources, may be said to be at the fore-front of current investigations, building on, and extending, the scope of study pertained in previous European excess heat projects such as Stratego and Heat Roadmap Europe. While the study of available excess heat from conventional sources has been conceived and conducted on the basis of several different approaches (for some European examples, see references [15-25], and for USA, see e.g. [26]), less attention has so far been given to that of unconventional or low-temperature sources (for a few examples, see references [27-29]). However, the rate of both mundane and scientific publications addressing the prospects and possibilities for excess heat recoveries from unconventional sources is rapidly increasing. Especially so for data centres, a contemporary topic that has been treated among others by [30-35], but also so for studies focussing on metro stations [36-41], as well as on waste water heat recovery [42-45].

Given this level of awareness, it is further very appropriate, in accordance with the main ReUseHeat project objective, to direct attention to non-technical barriers for the realisation of future excess heat recoveries. The inconvenient truth of the matter is, namely, that, historically and at current – despite high degree of technological maturity in heat distribution systems – very small fractions of present excess heat volumes available from conventional and unconventional sources are actually being recovered and utilised in large-scale applications. Persson and Werner [46] provided an account of annual excess heat volumes recovered in European district heating systems from industry sectors (including refineries) in 2008 (some 25 PJ annually), a fraction which, relative total primary energy input to the corresponding industry sectors (6.24 EJ), constituted less than half a percentage (0.4%) as an EU27 average.

This appropriateness is also underlined by the popular slogan, sometimes heard in contemporary excess heat discussions in Europe, that "there is enough waste energy produced in the EU to heat the EU's entire building stock", a postulate that should be taken with a grain of salt. No doubt, total volumes of rejected excess heat from all considered sources do approximate total end-use space and domestic hot water heat demands in residential and service sector buildings (roughly at some 10-11 EJ per year in EU28, for references see e.g. [47-50]), but in terms of practical utilisation of these assets, several delimiting factors come into play. This is one of the reasons why, in the context of this work – which primarily considers the alternative of large-scale recovery and utilisation by means of heat distribution infrastructures – the geographical correlation between source locations and the presence of such infrastructures constitute a key modelling feature.

In terms of modelling, further, input data for the three considered conventional sources (demo-sites), have generously been made available from the Heat Roadmap Europe project (latest update with data up to year 2014 [51]), why these sources have been excluded from the active modelling performed under T1.2, albeit being part of the performed spatial mapping.

The work presented in this report has been carried-out at the School of Business, Engineering and Science, at Halmstad University in Sweden during the period from October 2017 to November 2018 (revision during spring 2020). Apart from this documentation, and that of a conference presentation during the autumn of 2018 [52], final outputs for two of the modelled unconventional sources (metro stations and waste water treatment plants) was made publicly available on November 13, 2018, as operational layers at the PETA 4.3 (Pan-European Thermal Atlas, version 4.3) web map application, accessible at the Heat Roadmap Europe project web site [53]. As for the remaining unconventional sources, similar publications of final outputs at the PETA web map application, or other, is currently under evaluation.

Currently under evaluation, as well, is the possibility of presenting a second updated version of this revised D1.4 report at the end of the ReUseHeat project. The main objective for facilitating an updated version would be the opportunity to carry through a coherent comparison and validation and, if so found, proper adjustment of the potentials estimated in this step. At this later stage of the project, operational data and experiences from the four demo-sites, together with assembled responses from the Task 1.1 online survey (for more information, see refs. [54, 55]), and also a 2020 update of the Data Center Map (see further section 3.2), would all be readily available and beneficial for achieving highest possible accuracy in used data and generated outputs. The anticipated update has been integrated in the list of project deliverables as D1.9 and is due in March 2021.

1.3 Limitations

The notes given in this section on study limitations refer to those of general character, thus those concerning the work as a whole. For specific limitations and circumstances concerning the modelling and mapping of each respective source, see corresponding comments subsections under each category topic.

As a first note on general limitations, it is of importance to emphasise that the assessments presented in this report are to be viewed as indicative, first order, modelled potential estimates not to be confused with, or interpreted as, concrete viability evaluations or dedicated feasibility studies, none of which they are properly qualified to replace. For the latter two types of inquiries, the recommendation must be to always perform local on-site investigations in order to assess the prospects of any real-world excess heat recovery project.

Secondly, since the ReUseHeat project operates under the primary objective of utilising urban excess heat by means of large-scale recovery in district heating systems, a corresponding objective and preference has been maintained in the assessments of accessible excess heat potentials in this work. However, it should be noted that other technologies and applications for the recovery of urban excess heat certainly exists. A few examples of such technologies and applications could be those of direct on-site heat recoveries, low-temperature thermal networks (e.g. district energy grids), absorption cooling machines, as well as various applications of the Organic Rankine Cycle (ORC) for the production of electricity from low-grade heat. Indirectly, assessed available excess heat volumes in this study may be indicative also of such alternative applications, nevertheless, for accessible excess heat potentials, delimitation to current district heating areas has been the main approach withheld here.

Additionally, all energy conversions are associated with certain minor heat losses, be they efficiency factors in motor drives, transfer losses in heat exchangers, or operational losses in heat pumps. Throughout the modelling in this work such minor heat losses have been categorically neglected, which would imply that the found potentials may constitute marginal overestimates. On the other hand, since for all investigated sources, the study policy has been to consistently abide by the most conservative estimates, such neglect should be of less significance at the maintained level of modelling.

Finally, in an exercise like this, at this grand scale (EU28) and at the relatively limited resources at hand, generalisations (e.g. average values) and assumptions are unavoidable if to arrive at a coherent result at all. For the sake of scientific integrity and comprehensibility, therefore, the ambition in this report has been to state as correctly and clearly as possible all such made generalisations and assumptions, as well as all applied methods and approaches in general. It is our hope that, in the following, we have been able to satisfactorily and sufficiently live up to this ambition.

2 Methods overview*

The main methods used in this work may be characterised as semi-heuristic 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 a bottom-up quantification of available and accessible excess heat volumes at facility (or ground land area) level, volumes which are then viable for aggregation up to city, national and EU levels. An overview of main methods used for each of the seven modelled unconventional urban excess heat sources is given in Table 2.

Table 2. General overview of main methods used in the assessments of available and accessible urban excess heat from the seven unconventional sources.

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

As can be seen in Table 2, 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 alternative top-down approaches has 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.

While briefly mentioned above, it should be again made clear that all input data concerning the three included conventional excess heat sources (for the demo-sites), i.e. power plants, energy intensive industrial facilities, and Waste-to-Energy plants, have been retrieved from the Heat Roadmap Europe project. These potential assessments, which are also displayed at the PETA 4.3 web map application, have relied on similar methods and approaches as those performed here for the unconventional sources, essentially by use of publicly available carbon dioxide emission data at facility level combined with energy statistics and default recovery efficiencies. Since these assessments already are well-documented, no further account of these will be given here. For the most detailed documentations, see e.g. references [56, 57], and also [51] for a later application. Noteworthy, however, is that from the maximal 100% theoretically available excess heat volumes stipulated in the original assessments, since the target here explicitly is "accessible" volumes, only a fourth (25%) of these potentials have been considered here.

Overall, the work flow in T1.2 has principally followed that which was outlined in the first internal WP1 Gantt chart from November 2017. Accordingly, work initially consisted of literature reviews and data collection during the first five months of the project (October 2017 to March 2018), where after work on data preparation and analysis followed during the spring of 2018. By September 2018, the final potential assessments were being developed based on the conceived methods and the gathered data. In September 2018, the dedicated writing process of this report started, parallel with continued spatial modelling and validation procedures. During the last two months (October and November 2018), while increasing the pace of writing, all the results, i.e. the accessible urban excess heat potentials for EU28, have been finalised and successively summarised in tables, graphs, and maps etc.

The revision of this report has taken place mainly during the period from January to May 2020 and has been performed in collaboration between Halmstad University (Sweden) and Aalborg University in Denmark. The main contributions from Aalborg University refer to the work on food production facilities and food retail stores, while Halmstad University has contributed with the assessment for buildings in the residential sector. Halmstad University has also performed the final preparation and editing of the revised report.

2.1 Type processes*

In line with the decree formulated in the T1.2 work description, regarding classification and characterisation of typical processes (type processes) and technologies which represent the recovery of excess heat from the considered urban waste heat sources, Table 3 presents a schematic overview for the seven source categories.

Since a common feature for these sources is that they all may be characterised as low-temperature, hence the label "unconventional", all heat recoveries from these sources are perceived to take place by means of (large-scale) compressor heat pumps – with the exception of rejected heat from refrigeration processes in the food retail sector. The reason for this is that, for this sector, refrigeration has been modelled as taking place solely with trans-critical CO_2-systems, which reject heat at sufficiently high temperatures for direct recovery in district heating systems (for a more detailed account regarding this modelling, see further section 6.1).

By low-temperature is thus understood discharge of available excess heat at temperatures well below 50°C (in most instances rather in the interval of 5°C - 40°C), which, for its practical utilisation in district heating systems, requires the a necessary temperature lift (supply temperatures in 3rd generation district heating systems are on average above 80°C).

Table 3. Classification and characterisation of typical processes, temperatures, temporality properties, and technologies that represent the seven modelled unconventional excess 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	5°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

The temperature range given for data centres refers to electrical server room air cooling systems, while that of metro stations refers to the full annual temperature interval present over the year in platform air ventilation shafts (with 5°C representing a fixed low set-point temperature to avoid ice build-up on evaporator surfaces, see further section 4.1 Methods). 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). 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, while post-treatment sewage water from waste water treatment plants is expected, on average, not to fall below 8°C year round (12°C as an approximate average).

In terms of temporality, i.e. diurnal and seasonal variability, here primarily with reference to availability (not to temperature levels), four sources exhibit principally constant features, both on a daily and annual basis. The diurnal load in server stations 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 excess heat possibly recoverable from this source. For service sector buildings, essentially so with respect to offices, hospitals, schools etc., i.e. activities which in terms of intensity follow normal working-week rhythms, 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 3 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 in the context of this work. As can be seen, heat recovery from the first two source categories is conceived as taking place by means of air-to-water heat pump configurations, liquid-to-water for residential and service sector buildings and water-to-water for sewages, where the secondary side of these conversions refers to heated water circulated in the forward (supply) pipe of 3rd generation district heating systems (see further section 2.3.1 below).

2.2 NACE classification*

With reference once more to the T1.2 work description, where it is stated that "information will be collected at the NACE code level to identify the urban waste heat sources and a listing based on the NACE classification will serve as a means to associate temperature and temporality to each identified source", the following remark may be appropriate here.

At the time of forming the ReUseHeat consortia and writing the original project application (autumn of 2016 and winter of 2017), an offspring approach originally conceived in the Heat Roadmap Europe project, however only partially developed in that context (see e.g. [27]), was considered appropriate for the ReUseHeat project context and thus further elaborated. The idea of the approach was to use NACE classification Class Codes (Rev 2, 615 Class Code activities in all [58, 59]) and associate to each of these activities typical excess heat processes (type processes), that would entail information on e.g. temperature levels and temporality profiles. By such a procedure, it would be possible to determine and characterise excess heat potentials simply by knowing the corresponding NACE classification for any given activity.

However, the initial type process list was limited mainly to conventional excess heat sources, i.e. energy, industry, manufacturing, and waste management activity sectors, why work was carried out here to complement the original type process list with respect to low-temperature excess heat processes. For the seven considered urban excess heat sources considered in this study, the resulting type processes are those presented in Table 3, while the corresponding NACE Class Codes (together with Section, Division, Group Codes and Names) are those presented in Table 4.

It may be noted in this latter table, that for data centres it is somewhat unclear whether the stated Class Code is the only one referring to dedicated data centre activities, since a couple of other Class Codes may include such activities as well. Under Division 61 (Telecommunications), for example, Class Codes 61.20 (Wireless telecommunications activities) and 61.90 (Other telecommunications activities) may very well constitute such activity segments. This may also be the case for Division 62 (Computer programming, consultancy and related activities), Class Code 62.90 (Other information technology and computer service activities), as well as for some others under Division 63, particularly Class Codes 63.12 (Web portals) and 63.99 (Other information service activities n.e.c.).

For service sector buildings, since, in the context of this work, this source category comprises all activities of this sector, the complete list of EU28 service sector NACE Division Code activities, as outlined by Eurostat's Concepts and Definitions Database [60], are specified in Table 4. For a full account of all 292 Class Codes forming under these 48 Divisions, see reference [58]. For residential sector buildings, since no dedicated economic activity is associated to this sector, no NACE classification has been assigned to this source category.

Table 4. The studied seven unconventional urban excess heat sources by NACE (Rev 2) Classification. Source: [58, 60]

Source	**Section Code & Name**		**Division Code & Name**		**Group Code & Name**		**Class Code & Name**	
Data centres	J	INFORMATION AND COMMUNICATION	63	Information service activities	63.1	Data processing, hosting and related activities; web portals	63.11	Data processing, hosting and related activities
Metro stations	H	TRANSPORTATION AND STORAGE	49	Land transport and transport via pipelines	49.3	Other passenger land transport	49.31	Urban and suburban passenger land transport
Food production facilities	C	MANUFACTURING	10 11 12	Manufacture of food products, beverages, tobacco	10.1 to 10.9, 11.0, 12.0	For Group names, see Table 14 in section 5.1.1	All under the given Group Codes	
Food retail stores	G	WHOLESALE AND RETAIL TRADE; REPAIR OF MOTOR VEHICLES AND MOTORCYCLES	47	Retail trade, except of motor vehicles and motorcycles	47.1 47.2	Retail sale in non-specialised stores, Retail sale of food, beverages and tobacco in specialised stores	47.11, 47.19, 47.21 to 47.29	Retail sale in non-specialised stores with food, beverages or tobacco predominating. Other retail sale in non-specialised stores. Retail sale of fruit, vegetables, meat, meat products, fish, crustaceans, molluscs, bread, cakes, flour and sugar confectionery, beverages, and tobacco products in specialised stores. Other retail sale of food in specialised stores
Service sector buildings	292 Class Codes under 16 Section Codes within Division Codes: 33, 36, 37, 38, 39, 45, 46, 47, 52, 53, 55, 56, 58, 59, 60, 61, 62, 63, 64, 65, 66, 68, 69, 70, 71, 72, 73, 74, 75, 77, 78, 79, 80, 81, 82, 84, 85, 86, 87, 88, 90, 91, 92, 93, 94, 95, 96 and 99.							
Residential sector buildings	Not an economic activity.							
Waste water treatment plants	E	WATER SUPPLY; SEWERAGE, WASTE MANAGEMENT AND REMEDIATION ACTIVITIES	37	Sewerage	37.0	Sewerage	37.00	Sewerage

2.3 Definition of urban areas

The topic of how to define urban areas in Europe has been a matter of continuous debate and development. Historically, there has been no unified set of definitions whereby to perform uniform assessments as of the spread and distribution of urban areas among the 28 member states, since many of these countries have relied on nation specific measures and definitions. Only in the last couple of years, by means of a new (revised) system of urban/rural typologies [61], has this issue been principally resolved, however still by quite complex use of several different concepts in combination.

The new typology, in brief, incorporates a classification of square kilometre raster cells by criteria such as population density and contiguity (classes: rural, urban clusters, and urban centres), which provides input so as to define the degree of urbanisation at municipal level (LAU2). The degree of urbanisation is correspondingly defined by the three classes: rural areas, towns and suburbs, and cities. This information is then aggregated to the NUTS3 region level, at which the urban/rural typology is expressed in terms of corresponding rural regions, intermediate regions, and urban regions. For the main input data, i.e. population density at the square kilometre resolution, the new typology primarily looks for data on population distributions in registers, and, if not available, utilises LAU2 level population statistics which are downscaled, by various methods, to the raster grid level.

A completely different approach to define urban areas is feasible by use of high-resolution satellite imagery. This technique constitutes the core source of input data for the extensive Corine Land Cover datasets, which have been made publicly available at the European Environment Agency (EEA) in successive updates since 1990 [62]. Building upon the Corine Land Cover data, a subset consisting of four out of the regular 44 land use classes defined in the dataset, is used to produce the so-called urban morphological zones (UMZ) excerpt [63, 64]. The four selected 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).

2.3.1 Urban areas with district heating

For the identification of urban areas with district heating systems currently in operation, once more, previous work performed in the Heat Roadmap Europe project has been made available for the T1.2 studies. In the former, the 2006 urban morphological zones dataset for Europe [65], was used in combination with the Halmstad University District Heating and Cooling database, version 5 [66], to convert its original point-source information on district heating city centres to coherently distributed district heating urban areas. An account of the details concerning this conversion process is reported in [51], and the result (for the 14 EU28 member states studied in the HRE project), is available at the PETA 4.3 web map application (see operational layer named "Current DH systems (HRE4)") [53].

The resulting dataset layer of thus polygon-shaped urban areas, accordingly with one or more district heating system currently in operation, has been labelled the "UMZDH"-layer in the context of this work. Noteworthy, for Greece (EL), the original UMZ 2006 dataset was void of polygon data, why point-source data instead has been used for this country (this only so for the four sources considered in the original version. For the three additional sources considered in the revised version, no spatial mapping relative UMZDH areas has been performed for Greece). Some general information for the EU28 UMZDH-layer is presented in Table 5.

Hereby, it is made possible to investigate and determine the spatial coherency of current urban excess heat sources with that of current European district heating areas. As can be seen in Table 5, the input information available for these investigations include for EU28 a total of 3280 such urban district heating areas, which, within themselves, contain 4113 unique district heating systems. Thus, in order to distinguish between found total accessible excess heat potentials (see further section 2.4.3 below), and that which, by reference to distance from necessary recovery infrastructures, should be significantly smaller, spatial cross-referencing in a GIS constitutes a key method feature in this work.

Table 5. Number of urban areas with district heating systems (UMZDH) and total number of unique district heating systems in these areas. Sources: [65, 66]

MS	UMZDH [n]	District heating systems [n]
AT	327	473
BE	23	46
BG	21	22
CZ	370	394
DE	195	257
DK	407	458
EE	133	150
EL	3	5
ES	14	17
FI	149	179
FR	230	448
HR	18	18
HU	93	107
IE	2	2
IT	62	81
LT	35	37
LU	1	1
LV	35	38
NL	16	20
PL	379	424
PT	1	1
RO	70	74
SE	339	385
SI	54	56
SK	210	221
UK	93	199
Grand Total	**3280**	**4113**

For this purpose, a set of pre-defined distances have been applied, which would indicate whether a given source is located within (inside), within 2 kilometres, within 5 kilometres, within 10 kilometres, or beyond 10 kilometres (outside), of such current urban district heating areas (where the 2 kilometre mark is the default used for the outputs presented in this report). By subsequent selection, spatially weighted accessible excess heat volumes may hence be distinguished, which should reflect the practical accessibility level of any considered excess heat sources in terms of recoverability and utilisation. Local conditions act, in this way, as a mitigating factor with reference to found total levels of accessible excess heat.

The district heating systems referred to in the UMZDH-layer dataset, which reflect the majority of large EU28 systems and ~70% of all current systems (often approximated to some 6000 systems), are all anticipated to be associated with so-called 3rd generation operational characteristics (for a reference on district heating generations, see [67]). This implies supply temperatures in the order of approximately 75°C to 120°C, depending on the ambient temperature, which is reflected in the COP (Performance of Coefficient) factors for the modelled heat pump applications. This aspect is elaborated further in section 2.4.1 Principal heat pump theory below.

In short commentary, considering the study approach here described, it is recognised, also in response to some internal project discussions and comments, that the delineation of urban district heating areas by use of UMZ's is improvable. First, since an urban morphological zone in itself is defined as "a set of urban areas laying less than 200 meters apart", these zones may righteously be considered not to be directly representative of district heating areas. Second, although UMZ's realistically delineate urban areas from other land use classes, these zones are even less directly representative, or even linked, to the actual pipe network configurations of any given district heating system.

These are 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. However, experience and academic studies both teaches that, quite clearly, the feasibility of district heat distribution is directly proportional to population and heat densities [68], why assuming current systems to primarily have been built for operation in highly populated areas, i.e. urban morphological zones, makes, if not perfect, yet quite reasonable sense.

2.4 Basic concepts

This section presents a few basic study concepts which are applied homogenously within the study methodology, while specific concepts referring to each of the seven source categories are detailed under each respective method subsection.

2.4.1 Principal heat pump theory

As mentioned in section 2.1 above, all heat recoveries modelled for the considered unconventional urban excess heat sources in this work is perceived to take place by means of (large-scale) compressor heat pumps (with the exception of the food retail sector). Given that all considered sources may be characterised as low-temperature sources, discharging available excess heat at temperatures well below 50°C, the necessary temperature lift for its practical utilisation in 3rd generation district heating systems is thus assumed to be provided by such heat pump applications. Given this common feature, the following principles for heat pump operations are used uniformly throughout the study for all considered sources.

According to Dincer and Kanoglu [69], pages 22 – 26, the basic energy balance for a refrigeration cycle, equivalent to that of a heat pump, may be expresses as:

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

Where, in a heat pump, the heat transferable from the condenser (high temperature side) of the heat pump, Q_H (J), is the sum of the heat transferred to the evaporator (low temperature side) of the heat pump, Q_L (J), and the amount of work introduced to the process (electricity for a compressor driven heat pump), W (J). This basic principle, if neglecting any heat transfer or auxiliary equipment conversion losses, may be illustrated as in Figure 2.

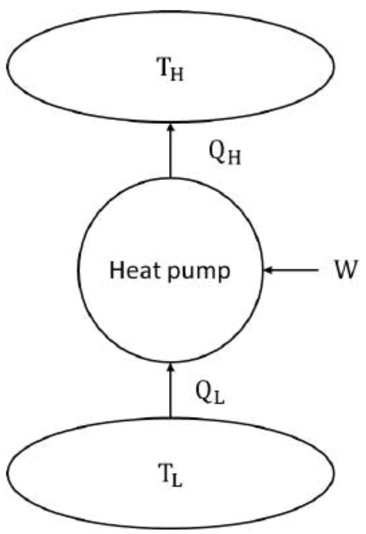

Figure 2. Simplified schematic of the vapour-compression refrigeration cycle. Source: [The authors].

From this, the practical COP (Coefficient of Performance) of a heat pump may be written as:

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

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:

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

If related to temperatures instead of to energy magnitudes, i.e. 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:

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

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 [-], i.e. the ratio of practical vs. theoretical performance, which provides an indication of the actual inefficiencies that are associated with real-world heat pump operations:

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

On the basis of these basic theoretical concepts for heat transfers in heat pumps, the main challenge of the modelling in this work has been to establish the magnitudes and temperature levels at which available excess heat from the considered source categories may be possible to recover. As shown above, in Table 3, in terms of temperature levels, this has been managed essentially by means of the identified type processes, which in turn builds on literature reviews. As for the corresponding energy magnitudes of available excess heat, unique approaches have been applied for each considered source, and these efforts constitute the much more laborious main body of work performed in T1.2.

In accordance with the above, and if ignoring minor transfer heat losses, the excess heat available for recovery from the considered sources may thus be viewed as principally corresponding to the heat that may be transferred to the heat pump evaporator, i.e. 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, gives an expression for the useful output of accessible excess heat (so termed in the context of this study) from the conversion:

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

Here it might be noteworthy to realise that, at a constant level of available excess heat, the useful output of accessible excess heat will decrease with increasing COP values, which might appear awkward at first. However, increased COP values indicate that less (compressor) work is required to drive the heat pump process, which can be observed in Figure 3 (where Q_L is kept constant), but with the consequence of generating a smaller volume of useful heat output.

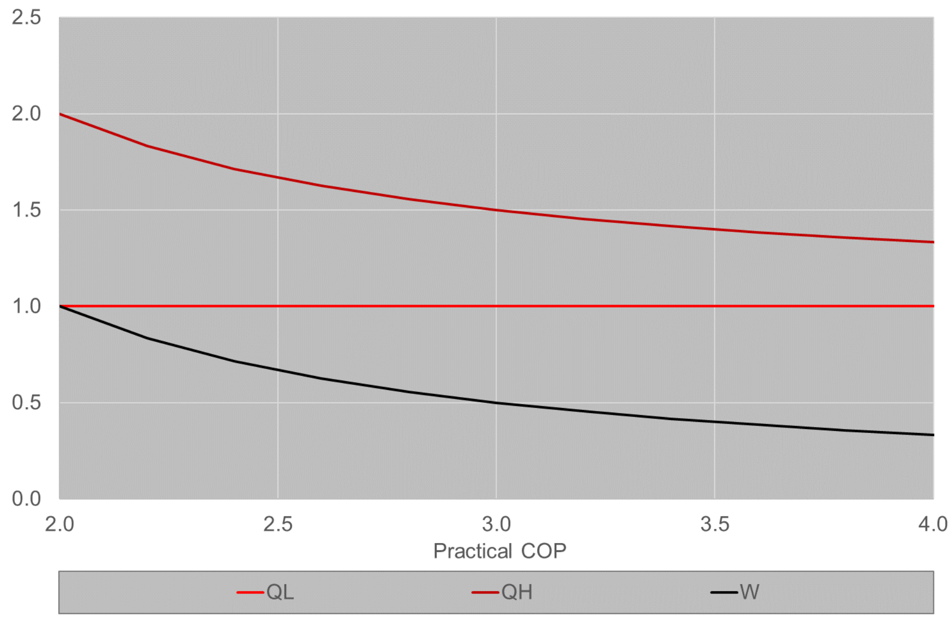

Figure 3. Basic relationship between the practical COP, Q_H, and W, under the condition that Q_L is kept constant at a given magnitude of energy.

To facilitate an opportunity to evaluate the impact of different COP values on the assessed accessible excess heat potentials, as a feasible sensitivity analysis parameter, three fixed values for the practical COP has been maintained throughout the modelling: 2.5, 3.0, and 3.5. The results presented in the main of this report attaches to the 3.0 value by default, however, outputs for the other two COP values are available, and for selected outputs also presented in section 15 Appendix.

In view of the source temperature ranges given in Table 3, as well as the temperature range stated for supply pipe temperatures in 3rd generation district heating systems, Equation (3), (4), and (5), may be used to establish a general understanding of the anticipated average Carnot efficiency of the modelled heat pump conversions. If, for example, considering post-treatment sewage water, supposedly rejected at annual average temperatures of 12°C (see further section 9.2 below), and relating this to an *ad hoc* annual average supply pipe temperature of 85°C, the theoretical COP is found at 4.9. In practice, as found in the Swedish input data used for the waste water regression model presented in section 9.2.3, the average practical COP for the 20 Swedish facilities was 3.0. Hereby, an average Carnot efficiency for this source category is conceivable at 61%.

With respect to heat pump operations, additionally, which in vapour-compression cycles all rely on the 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. For any real-world excess heat recovery project, however, needless to say, it should be evident that such considerations always must be addressed.

2.4.2 Available excess heat

To end this methods overview section, a few orderly words on two concepts that has already been somewhat randomly introduced in the above, however, two concepts, which given their most profound significance for the chief conception of this work, each deserves a proper account.

First, let it be clear that what is termed here as *available* excess heat refers to heat available at a source and recoverable at the evaporator side of any given compressor heat pump, thus corresponding to Q_L. The physical nature of available excess heat to be recovered at each of the considered source categories is indicated in Table 3, column

"Recovery type", and is further described under each respective category section in the following.

The significance of this concept is that the assessed potentials for available excess heat is independent of any specific utilisation technology, meaning that these estimations simply states what magnitudes of recoverable excess heat that supposedly is out there irrespective of which or whatever means by which it might be recycled and reused. This may be of importance and relevance if evaluating possibilities for excess heat recovery technologies other than those investigated here.

Available excess heat may further be subject to temporal conditions, i.e. diurnal and seasonal variations, depending on e.g. source category, operational characteristics, location, time of year, as well as other ambient circumstances. Where appropriate, such circumstances have been considered in the modelling of this work.

2.4.3 Accessible excess heat

Secondly, *accessible* excess heat, thus corresponding to Q_H, is understood here as that heat which is accessible at the secondary side of any given compressor heat pump, i.e. that heat which is rejected from the condenser as the sum of available excess heat and electric energy (W) introduced to the process.

Since, when strictly considering large-scale utilisation in district heating systems, no such heat pump process is conceivable unless a real cooling source is in contact with the condenser to receive the heat, i.e. the supply pipe of a given system, the term "accessible" is used here also to denominate realistically recoverable volumes of available excess heat. For this end, the UMZDH-layer and the five distance criteria mentioned above in section 2.3.1, occupies a central position in the methods framework built in response to the objectives of the T1.2 assignment.

The distinction of accessible excess heat, in relation to that of available excess heat, was in fact inspired by the formal wording of the given T1.2 assignment, which in the GA expressively states as its objective to assess the "accessible" urban waste heat potential. While contemplating more deeply on this wording, the insight eventually arrived that a distinction between the two concepts was both appropriate and necessary given the nature of the study.

The significance, finally, of the concept of accessible excess heat, in addition to the just mentioned direct dependency on vicinity to present heat distribution infrastructures (modelled in this work), is that is allows identification and discussion of other factors that might moderate, or even hamper, the realisation of excess heat utilisation projects. When for example, as done here, considering compressor heat pumps as mediator technologies for low-temperature excess heat recoveries, electricity prices, energy tax regimes, environmental constraints, as well as general operator strategies (none of which are modelled here), may all prove highly influential on the viability of such projects. By distinguishing between available and accessible excess heat, a vocabulary is given which recognises that the presence of an asset is something quite different from the marketing of a product.

3 Data centres

Excess heat from data centres are derived mainly from cooling processes of IT (Information Technology) equipment installed in the server halls, i.e. by 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. Davies et al. [29] provides an overview of the typical temperature levels at which different components and processes in a data centre emits heat, an overview that has been freely interpreted and presented in Table 6.

Table 6. Typical temperature levels of emitted heat from different data centre components and processes. Source: Free interpretation of Fig. 2 in [29]

Component	Temperature [°C]
Processors	80
Memory chips	70
Liquid cooling	50-60
Storage devices (disk drives)	40-50
CRAC/CRAH return air	25-35
Chilled return water	15

Two main cooling technologies are applicable for use in contemporary data centres today: air cooling or liquid cooling systems, as also indicated in Table 6. A majority, however, if not all, of currently operating data centres in Europe are equipped with air cooling systems, i.e. CRAC (computer room air conditioners) or CRAH (computer room air handlers), which means excess 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 excess heat recovery temperatures are higher, typically in the range of 50°C – 60°C.

Wahlroos et al. [32], suggests that the IT-equipment electricity use in a regular air-cooled data centre correlates strongly with its electricity use for cooling processes (for HVAC use (Heating Ventilation Air Conditioner)), and that between them, a rounded factor two by one constitute the average relation. There are other indications in the literature as for the share of total electricity use used for IT-equipment operations. Lu et al. [70], for example, suggests that more or less all power consumed in a data centre (97%) could be captured in the form of excess heat. To maintain a conservative attitude, however, it is assumed here – as a modelling set-value – that 65% of total data centre electricity use is designated for IT-equipment operation, while 35% is anticipated to be used for cooling processes.

It is further noteworthy, that data centres normally operate with none or only marginal temporal variations. In this respect, Wahlroos [32] states that the combination of server backup traffic (night-time) and server service traffic (daytime), form a "uniform traffic profile", equally spread out over the diurnal 24-hour cycle as well as over the annual cycle. Hereby, it may be concluded that data centres operate on a continuous basis which makes them very suitable as stable excess heat sources.

In terms of efficiency measures, there are today a whole series of concepts, or performance indicators, that are used within the field of data centres to express the resource and energy effectiveness of their operations. Albeit none of them are actively used in this work, due to a general lack of sufficient data by which to establish them at facility level (see further section 3.2), the PUE (Power Usage Effectiveness) and the ERE (Energy Reuse Effectiveness) may both be mentioned as highly relevant from a perspective of excess heat recovery (for further references see e.g. [32, 71-73].

The general experience in search and pursuit of quantitative, facility level, data for the intended bottom-up modelling of data centre excess heat potentials in this work, is that a high level of confidentiality and secrecy characterises this sector. Despite repeated efforts and various approaches, detailed facility data on parameters such as installed power capacities, server hall floor areas, or even correct geographical coordinates in some instances, has been principally impossible to find. The experience is in fact that this reluctance to share site specific data appears to be symptomatic, a tendency perhaps to be expected given the vulnerability and importance of such communication and information infrastructures. In the context of this study, consequently, the modelling of potentials for this source category has had to resort to alternative approaches.

3.1 Methods

The original plan intended for the assessment of available excess heat from data centres was, in brief, to use site specific data on e.g. installed IT-equipment capacities together with information on annual operating hours and assessed shares of electricity used for IT-equipment, as indicated above. This, combined with information on geographical coordinates for each considered facility, would allow bottom-up assessments of excess heat potentials at urban, national, and EU28 scale levels.

For this purpose, a first requisite was to identify and retrieve data on the current population of European data centres and their geographical locations. After some inquiries, among which, among others, the European Commission Code of Conduct for Energy Efficiency in Data Centres initiative [74, 75] was considered, a commercial dataset from the Data Center Map assembly [76] was purchased in April 2018 [77]. Upon closer inspection, albeit counting some 1300 EU28 operational data centres, this dataset contained none of the sought quantitative data parameters needed to fulfil the initial intentions. Not even after an attempt to complement the dataset by a laborious manual procedure, utilising e.g. web searches, Google Earth etc., was it possible to gather sufficient data for the conceived modelling approach to be feasible, why eventually, it had to be abandoned. For further details regarding the dataset and the work performed to improve it, see section 3.2 below.

To still proceed, an alternative approach, based on the idea to use statistical information on member state total final consumption electricity use, readily available from various sources, in combination with literature references on the historical development of data centre electricity use (as fractional shares of such totals), was chosen. Koomey [78] estimated, on a global scale, that data centres already in 2010 accounted for 1.1 – 1.5% of the world's total final electricity consumption. By cross reference to the IEA (International Energy Agency) energy balances 2016 [79], for the same year (2010), where the world´s total final consumption of electricity is stated at 19,839.6 TWh (71.422,6 PJ), the given range would indicate a total data centre electricity consumption volume in the interval of 218 – 298 TWh (785 – 1073 PJ) for the given year.

This interval is in fair correspondence with statements made in a 2013 report from the Digital Power Group [80], where a graph indicates that world data centre electricity use would be approximately 300 TWh (1080 PJ) annually (however, assumedly for a later year than 2010). For Europe, Bertoldi et al. [81], assessed that 56 TWh (201.6 PJ) of electricity was used in data centres during 2007. In a more recent publication [82], 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 7. Note that the two far-right columns in this table have been added to the original table.

Table 7. European data centre final consumption electricity use as estimated in various sources and compiled by Avgerinou et al. in [82]. EU28 final consumption electricity use as reported in [79]

Year	Reference	Data Centre FC Electricity [PJ/a]	EU28 FC Electricity (IEA) [PJ/a]	Share [%]
2000	Koomey (2011)	65.9	9104.3	0.72%
2005	Koomey (2011) and Whitehead (2014)	148.7	10027.3	1.48%
2007	Bertoldi (2012)	201.6	10269.7	1.96%
2010	Whitehead (2014)	261.0	10233.2	2.55%
2020	Bertoldi (2012)	374.4	10233.2[a]	3.66%

[a] This volume refers to data for year 2010. For 2014 the corresponding volume was 9744.4 PJ (2707 TWh).

According to Whitehead et al. [83], also referenced in Table 7 ("Whitehead (2014)"), the electricity consumption of "Western European" data centres was assessed to 72.5 TWh (261.0 PJ) for the year 2010. By cross reference once again to the world energy balances of the IEA [ibid], the total final consumption electricity volume for EU28 was 2,842.6 TWh (10,233.2 PJ) in this year, which would render a data centre share of total EU28 final electricity consumption of approximately 2.6%.

If plotting these numbers in a graph, as in Figure 4, it becomes clear that the share of data centre final consumption electricity use out of total volumes, relative the sector electricity use, evolves linearly and should be found at some 350 PJ for the year 2018 (approximately at a 3.5% share).

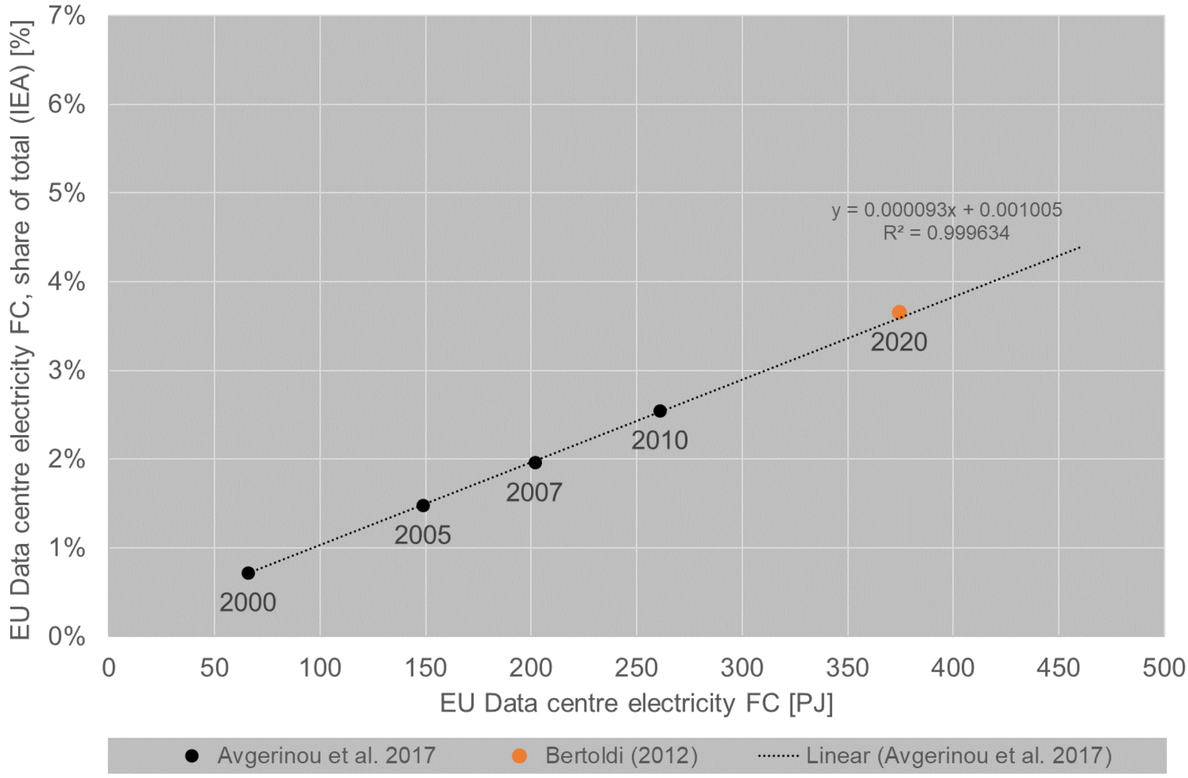

Figure 4. Graphical representation of European data centre final consumption electricity use as estimated in various sources and compiled by Avgerinou et al. in [82]. EU28 final consumption electricity use as reported in [79].

Based on the above stated circumstances, the excess heat potential from European data centres have been modelled on the member state national level only. Potentials of available excess heat (Q_L) constitute 65% of final consumption electricity volumes used in data centres, volumes that are assessed as 3.5% shares out of total national final consumption electricity use (Eurostat, 2016 [84]). The modelling thus assumes that all cooling processes of IT-equipment in these data centres are performed by means of air cooling systems.

For the georeferenced set of data centres retrieved from the Data Center Map database, a spatial analysis was performed by which to determine the location-based vicinity of each facility to urban district heating areas. Accessible excess heat (Q_H) potentials have further, as for all considered source categories, been calculated for the three default practical COP levels of 2.5, 3.0, and 3.5.

3.2 Data

In regards to electricity consumption data that would reflect the usage in data centres, a complementary check was performed for the year 2015 through the Eurostat NACE Rev.2 activity dataset [85]. Despite significant degree of incompleteness at member state level, and for data years other than 2015, this dataset was downloaded with reports for electrical supply, use, and end use, volumes specified for NACE Section Code J (Information and

Communication), and its underlying Division Codes 58 (Publishing activities), 59 and 60, bundled (Motion picture, video, television programme production; programming and broadcasting activities), 61 (Telecommunications), and 62 and 63, bundled (Computer programming, consultancy, and information service activities).

For the year 2015, the Eurostat dataset reports for EU28 a total electricity use volume for Section Code J of 215.9 PJ, of which 13.7 PJ for Division Code 58, 20.4 PJ for Division Codes 59 and 60, 114.4 PJ for Division Code 61, and 67.5 PJ for Division Codes 62 and 63. Due to this bundling of divisions, however, it was not possible to distinguish explicitly the final electricity consumption for Division Code 63, Information service activities, as discussed in section 2.2 above and elaborated in Table 4.

If representative for the electricity used in data centres, which is questionable, the total section volume of 215.9 PJ is clearly lower than that anticipated above and as outlined in Figure 4. However, it must be stressed that it remains unclear whether this volume is applicable to data centre operations at all, which is the main reason why this dataset was not used further in the modelling here.

By a selection of EU28 data centres from the (world) Data Center Map dataset [77], retrieval of EU28 member state electrical final consumption data for the year 2016 from Eurostat [84], and the abovementioned 3.5% share allocation approach, the metrics used for modelling data centres in this work are as presented in Table 8.

Table 8. Number of EU28 data centres as reported in the Data Center Map dataset, total final consumption electricity use for the year 2016 (Eurostat), and assessed data centre final consumption electricity use. Sources: [77, 84]

MS	Data centres [n]	Total El FC (2016, ES) [PJ]	Data centre El FC (at 3.5% of total FC) (2016, ES) [PJ]
AT	17	223	7.8
BE	32	295	10.3
BG	20	104	3.6
CY	13	16	0.6
CZ	24	202	7.1
DE	203	1863	65.2
DK	29	112	3.9
EE	10	26	0.9
EL	14	192	6.7
ES	59	837	29.3
FI	18	291	10.2
FR	147	1593	55.7
HR	5	55	1.9
HU	8	134	4.7
IE	22	92	3.2
IT	67	1030	36.0
LT	11	35	1.2
LU	15	23	0.8
LV	17	23	0.8
MT	8	8	0.3
NL	97	380	13.3
PL	31	478	16.7
PT	26	167	5.8
RO	48	156	5.5
SE	53	459	16.1
SI	7	47	1.6
SK	14	90	3.1
UK	254	1094	38.3
EU28	**1269**	**10023**	**350.8**

As can be seen, the Data Center Map dataset contains records of 1269 data centres located in EU28, a number which must be recognised as indicative only. According to information received at purchase, input data is gathered mainly by provider contributions, i.e. data centre operators that voluntarily decides to become members of the Data Center Map community, and in fewer cases by manual addition by the map administrators. Data has been gathered on a world-wide basis since 2007, but the dataset offers no means by which to evaluate the extent of coverage, i.e. the degree by which currently operational data centres are included or not. For this reason, there may be more data centres in EU28 today, than those stipulated in the used dataset.

Another, perhaps more significant shortcoming of the dataset, is that it entails no quantitative data parameters by which to calculate excess heat potentials at site level. Upon purchase, this characteristic was not fully communicated, why Halmstad University arranged a special assignment during the summer of 2018, with the purpose of gathering such quantitative data by means of other sources. As can be seen in Figure 5 and Figure 6, the success of this laborious effort must admittedly be said to have been only marginal.

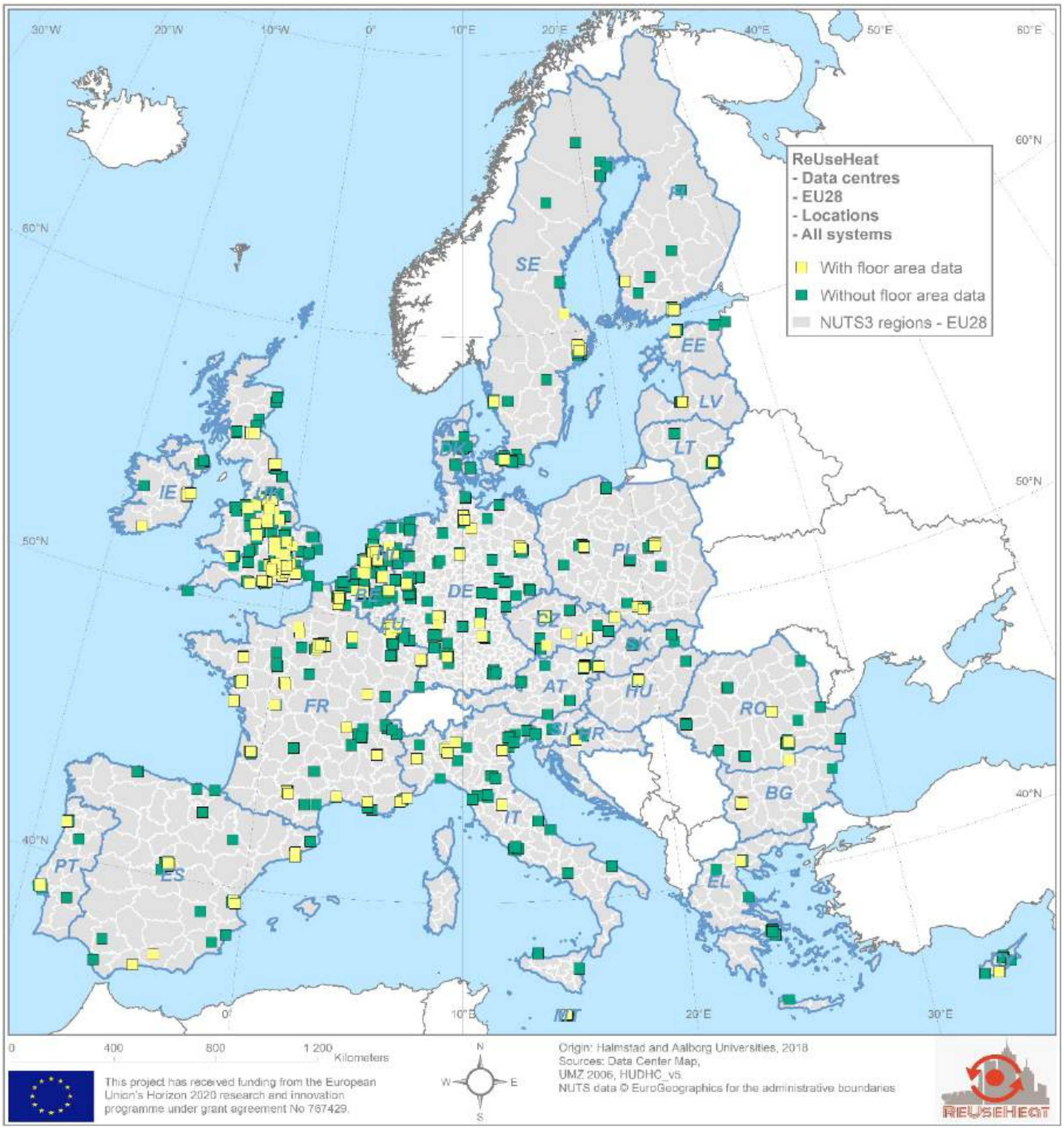

Figure 5. Locations of 1269 EU28 data centres, with indication of facilities for which floor area data was possible to find.

By using embedded web page links to each facility, included in the dataset, and so-called "profile" information stated at these, plus additional internet searches (Google Earth etc.), information on data centre floor areas were gathered for 266 of the 1269 facilities (Figure

5), and likewise for installed total electrical capacities in 63 instances (Figure 6). For a total of 155 facilities, no or irrelevant geographical coordinates (typically for a city centre, a local post office or the like) were given in the original dataset. Correction of these coordinates were also part of the special assignment, albeit it must be underlined that the exactness of some stated coordinates still remains diffuse.

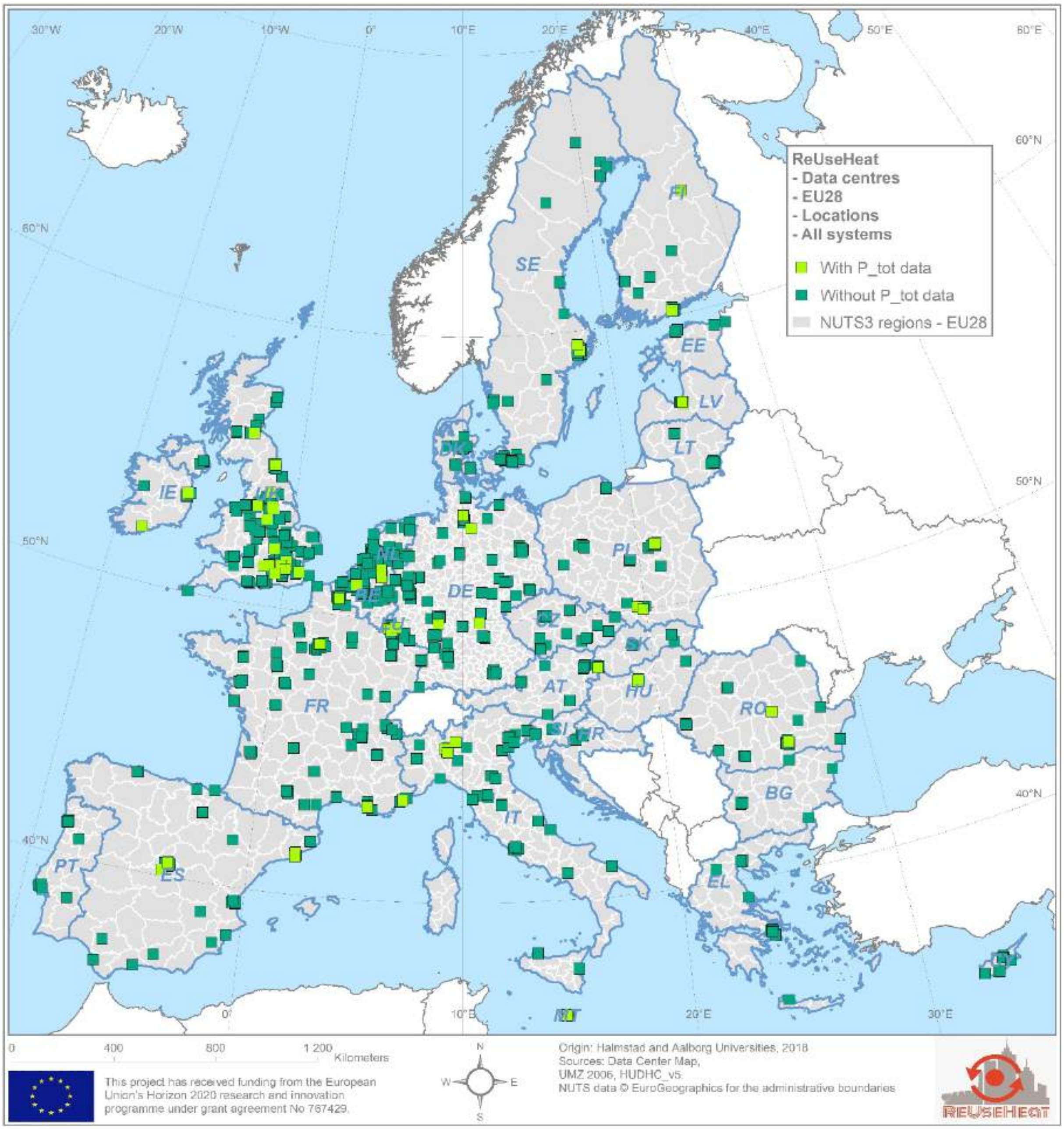

Figure 6. Locations of 1269 EU28 data centres, with indication of facilities for which installed electric capacity data was possible to find.

Due to this scarcity of quantitative data at facility level, the original intent of developing a correlation model with e.g. floor areas as independent variable and installed electrical capacities as dependent variable, had to be abandoned. The gathered data for these two parameters, although limited, would principally have allowed for such a conduct. However, for this approach to be practically viable, data on floor areas would have had to be available for all facilities, something which, as stated, was not possible to establish.

3.3 Results

Thus keeping in mind that the results from this modelling were rendered in a top-down manner, Table 9, outlines the available and the accessible annual excess heat volumes estimated for all 1269 facilities. Available excess heat (Q_L) constitute 65% of the 3.5% shares of final consumption electricity volumes stated in Table 8, and accessible excess heat (Q_H) is here presented for the case of a practical COP of 3.0.

In the two far-right columns of Table 9 are indicated what is assessed as specific corresponding quantities per site, on average. These numbers are included here for reference, however, since the modelling considers no actual site-specific information (such as floor areas, installed power 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 highly speculative and indicative only.

Table 9. Available excess heat as 65% of final consumption electricity used in 1269 EU28 data centres and accessible excess heat at practical COP of 3.0. Anticipated annual average excess heat volumes per facility (indicative only)

MS	QL (65%) [PJ]	QH COP3.0 [PJ]	*QL by facility (65%) [TJ/DC]*	*QH by facility COP3.0 [TJ/DC]*
AT	5.1	7.6	*298*	*447*
BE	6.7	10.1	*209*	*314*
BG	2.4	3.6	*118*	*178*
CY	0.4	0.5	*28*	*42*
CZ	4.6	6.9	*191*	*287*
DE	42.4	63.6	*209*	*313*
DK	2.6	3.8	*88*	*132*
EE	0.6	0.9	*60*	*90*
EL	4.4	6.6	*313*	*469*
ES	19.0	28.6	*323*	*484*
FI	6.6	9.9	*368*	*552*
FR	36.2	54.3	*246*	*370*
HR	1.3	1.9	*251*	*376*
HU	3.0	4.6	*380*	*570*
IE	2.1	3.1	*95*	*143*
IT	23.4	35.1	*350*	*524*
LT	0.8	1.2	*73*	*109*
LU	0.5	0.8	*35*	*52*
LV	0.5	0.8	*31*	*47*
MT	0.2	0.3	*22*	*32*
NL	8.7	13.0	*89*	*134*
PL	10.9	16.3	*351*	*526*
PT	3.8	5.7	*146*	*219*
RO	3.5	5.3	*74*	*111*
SE	10.4	15.7	*197*	*296*
SI	1.1	1.6	*152*	*229*
SK	2.0	3.1	*146*	*219*
UK	24.9	37.3	*98*	*147*
EU28	**228.0**	**342.0**	***176***	***265***

In terms of available excess heat, some 228 PJ of annual energy constitute the potential assessment for EU28. Germany, France, United Kingdom, and Italy are the four member states that, with regards to total volumes, represent the largest potentials. Albeit not further elaborated here, in specific terms (per capita), member states like for example Sweden, given a total population of some 9.6 million in 2016, appears to reach an anticipated potential in the order of ~1.1 GJ per capita.

Correspondingly, 342 PJ of annual energy constitute the full accessible excess heat potential according to the performed modelling (at practical COP of 3.0), however, this number is quite insignificant if there are no heat distribution infrastructures in place whereby to utilise the recovered excess heat. If thus considering spatial coherency, i.e. an adjustment of the found potentials by local conditions and vicinity to current urban district heating areas, here presented for the default of inside or within 2 kilometres of such areas, the results are as presented in Table 10.

Table 10. Number of data centres, final consumption electricity use, available and accessible excess heat for 997 EU28 data centres inside or within 2 kilometres of urban district heating areas.

MS	Data centres (2km) [n]	Data centre El FC (at 3.5% of total FC) (2016, ES) [PJ]	QL (65%) [PJ]	QH COP3.0 [PJ]
AT	16	7.3	4.8	7.2
BE	29	9.3	6.1	9.1
BG	19	3.5	2.2	3.4
CY	0	0.0	0.0	0.0
CZ	22	6.5	4.2	6.3
DE	187	60.1	39.0	58.6
DK	28	3.8	2.5	3.7
EE	10	0.9	0.6	0.9
EL	1	0.5	0.3	0.5
ES	36	17.9	11.6	17.4
FI	17	9.6	6.3	9.4
FR	124	47.0	30.6	45.8
HR	4	1.5	1.0	1.5
HU	8	4.7	3.0	4.6
IE	21	3.1	2.0	3.0
IT	39	21.0	13.6	20.5
LT	9	1.0	0.7	1.0
LU	7	0.4	0.2	0.4
LV	17	0.8	0.5	0.8
MT	0	0.0	0.0	0.0
NL	62	8.5	5.5	8.3
PL	29	15.7	10.2	15.3
PT	13	2.9	1.9	2.8
RO	47	5.3	3.5	5.2
SE	45	13.6	8.9	13.3
SI	7	1.6	1.1	1.6
SK	11	2.5	1.6	2.4
UK	189	28.5	18.5	27.8
EU28	**997**	**277.5**	**180.4**	**270.6**

Here it may be observed that most (997) of the 1269 EU28 data centres considered are in fact located inside or within 2 kilometres of urban district heating areas (79%), from which it follows that both available and accessible excess heat potentials are only marginally reduced by this limitation. Some 180 PJ of available excess heat may therefore be regarded as a benchmark value for feasible recoveries from EU28 data centres. At a practical COP of 3.0, the corresponding annual volume of accessible excess heat reaches approximately 270 PJ. For the corresponding results for practical COP values of 2.5 and 3.5, see Table 57 in appendix 15.2.

If assuming that the excess heat from these data centres is recovered at the low-range temperature value of 25°C, see Table 3, and further relating this to an *ad hoc* annual average supply pipe temperature of 85°C for 3rd generation district heating systems, a theoretical COP value would be found at 5.9, thus indicating an average Carnot efficiency for this source category at 50%.

3.4 Comments

Regarding the modelling of excess heat potentials from data centres in this work it may first be noted that a basic assumption is that electricity used for dedicated cooling purposes does not contribute to the excess heat generated at a data centre. This is to say that it is understood here that electricity used for cooling purposes (or other energy sources used for such purposes) does not give rise to recoverable emissions of excess heat. Recoverable excess heat is thus conceived as that heat, which is removed from the server hall itself, which excludes heat that might be emitted by the components of the cooling system itself (compressor motors, piping etc.).

Secondly, when considering installations for excess heat recoveries in data centres, the safety aspect, i.e. the guaranteed preservation at all times of stored and managed data must be recognised as a key priority. Heat recovery systems, which might be subject to operational failures and other interruptions, should therefore be designed so as to not hamper or jeopardise server operations during such occasions.

For further reading on excess heat recovery from data centres, see for example [86, 87], and for some real-world examples, see [88-90]. Regarding environmental aspects of excess heat recoveries from data centres viewed from a life-cycle perspective, see e.g. Whitehead et al. [91].

4 Metro stations

Excess heat from metro stations are derived from station platform and tunnel exhaust ventilation air shafts, i.e. by the removal of sensible and latent heat from air heated mainly from electricity used to drive the train carriages, from auxiliary systems, and from heat dissipated upon braking as trains stop at a platform. The main modelling assumption in this work is that, as air with outdoor conditions enter the platform area, its temperature increases due to heat generation from by the transportation system, with the consequence that its relative humidity decreases, since the air water content is assumed constant through this phase. Heated moist air from the platform is then withdrawn through ventilation shafts located within the vicinity of the platform, where heat is extracted at a heat pump evaporator surface before exiting into the ambient surroundings.

In terms of references, a more extensive literature review was performed in order to provide an initial orientation and insight into what previous and contemporary research of metro systems has learnt. For this purpose, a Scopus search using a combination of keywords (main keyword "Metro", independently paired with others such as e.g. "ventilation", "heat", and "heat recovery"), identified a set of recurring topics whereby current research in the area may be categorised. These areas are; energy efficiency and audits; thermal comfort; air quality; heat recovery; and hazardous aspects typically related to ventilation systems.

Regarding the first topic (energy efficiency and audits), aspects such as frequency control, i.e. introduction of variable speed of electrical fan engines in order to distribute power load according to distribution of passengers, hence to decrease electricity demands, has been assessed by Yang et al. [92]. In a parametric study, Mortada et al. [93], establishes where heat is generated at a metro station (e.g. by electricity used in trains and auxiliary systems, and conversion of kinetic energy when braking), while also investigating possibilities with regenerative braking. In [94], a schedule approach for energy efficient regenerative braking in metro systems is presented, while regenerative braking is considered also from an energy efficiency perspective in [95, 96].

From an energy efficiency perspective, further, field measurements of improved air conditioning systems, and possible energy efficiency gains, have been assessed for a metro station in Beijing by Wang et al. [97]. In another study [98], improved control of air conditioning systems in combination with platform doors, as a means to decrease electricity demands, is assessed. On a similar theme, Yang et al. [99], investigates improved platform screen doors as an energy efficiency measure. In reference [100], a predictive model to reduce energy demands from ventilation systems, applied to a metro station in Barcelona, is presented. An energy audit for non-traction energy is further presented in [101]. Casals et al. [102], summarises the research project SEAM4US, a project that aimed at increasing energy efficiencies of metro stations through implementation of intelligent energy management systems. Another approach, that of a statistical indicator model for energy benchmarking of metro station through energy use intensity, is presented [103]. In [104], also, an assessment to minimise costs through reduced use of ventilation, while still retaining healthy indoor air quality, is presented.

As for the second topic (thermal comfort), aspects such as field measurements of air temperatures and humidity for stations at different depth has been performed by Assimakopoulos and Katavoutas in [105]. The same authors also presented an assessment of thermal comfort conditions in metro stations [106]. In [36], a study assessing thermal comfort of metro systems within the United Kingdom is presented.

Thirdly (air quality), a topic that has received quite a lot of attention given its direct influence on aspects such as human health, is studied mainly from the perspectives of air pollutants, particle matter etc. Lee et al. [107], presents a predictive model to assess how particulate matter concentrations from outdoor air influence indoor air quality of a metro station, while Xu et al. [108], presents a literature review concerning air pollutants, particle matters and volatile organic compounds in metro station environments. In reference [109] an assessment of air quality for three European metro systems is presented, and Moreno et al. [110], performed a high resolution air quality assessment on differently designed station platforms in Barcelona. In relation to thermal comfort, Ampofo et al. [36, 37], presents a generic heat load model for metro station which states, through theoretical analysis, that over 80% of heat derives from the braking mechanism of the rolling stock.

Regarding the fourth topic (heat recovery), methods of potential technical installations for heat recovery are given by e.g. Gilbey et al. [38]. In references [111, 112], design criteria for metro ventilation systems are considered, albeit not categorised as heat recover per se, but still essential in this context. The same may be said for a study by Krusyuk et al. [113], which concerns the inspection of ventilation system operation within metro systems. Ninikas et al. [39], studied heat recovery from air in underground transport tunnels with air source heat pumps as recovery technology. In [40], Chai et al. presents a similar analysis of excess heat recovery from metro systems by utilisation of air source heat pumps. Finally, Davies et al. [41], provides a description of an implemented heat recovery scheme, by use of air source heat pump connected to a metro station, which supplies heat to a nearby housing area in the United Kingdom.

As for the fifth topic (hazardous aspects), the literature review identified only one paper. This study assessed air flow structures of non-mechanical ventilated systems related to chemical or bacteriological attacks, and can be found in [114].

In general, as for a definition of what is here referred to as metro systems, it is recognised that several modes of public rail transportation are operated in cities around the world, which has been outlined and defined by the American Public Transportation Association (APTA) [115]. In this context, the mode "heavy rail", a mode of transit service operated on an electric railway with the capacity for heavy volumes of traffic, high speed, and rapid acceleration, constitute the study preference. By this terminology, heavy rail systems are conceived here to include ordinary metros, subways, and rapid transit system (or rapid rail). In addition, city, or country, specific names occurring in some instances, such as for example the "London Underground" and the German "Untergrundbahn" (U-Bahn), are likewise included. Other modes, such as "light rail" and "commuter rail", may exist in parallel to heavy rail, however, such modes are excluded here. Metro systems, moreover, typically operate underground within a city centre, but well over half of a metro network may operate aboveground at surface or elevated levels [116].

4.1 Methods

For the source category of metro stations, two main method approaches are used in combination to arrive at the sought available and accessible excess heat recovery potentials. The first of these approaches refers to a model by which to assess the volumetric potentials themselves, based on e.g. meteorological data and theoretical concepts by which modelling parameters are established (see section 4.1.1 below). The second approach concerns spatial mapping, which has consisted in gathering of geographical information, i.e. georeferencing, of current metro stations in EU28 (see section 4.1.2).

A total of 37 EU28 cities, as detailed in Table 11, has been identified in this context as operating heavy rail systems at current. If extending the scope also to non-EU membership states, as presented by Caroli in a data visualization scheme for metro systems in European cities [117], a total of some 57 cities are anticipated to have metro systems in operation.

Table 11. Listing of the 37 metro cities included in this study.

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	

Indicative of some general ambiguity concerning the actual number of European metro cities, Metrobits [118], an independent source compiling data about metro systems worldwide, further indicate that there are as much as 63 cities within EU membership states. Somewhat more moderately, ERRAC (The European Rail Research Advisory Council) and UITP (International Association of Public Transport) [119], together report that Europe contains 45 metro systems, in this case however it is unclear which cities it concerns.

Metro stations in the 37 cities have been identified through use of official metro maps for each respective city. Metro network extensions, i.e. stations in planning or construction phases, have been omitted from the analysis. In the case of more than one metro line utilising the same station, only one entry has been added to the list of total metro stations. Depth of a metro substation is not considered, irrespective of it being an underground or an aboveground station.

4.1.1 Model parameters

The method presented in this chapter aims at determining the potential heat power capacity, $\dot{Q}_L$ [W], available for heat recovery in heavy rail stations. A temporal aspect is integrated in the method by utilisation of meteorological climate data on a monthly average basis for each of the represented geographical locations. Collected climate data consists of average monthly outdoor temperatures (t) and relative humidity (RH), as found in [120, 121], and specified in Table 58 in appendix 15.3.

For the outdoor conditions, the saturated vapour pressure, e_s (Pa), is determined according to:

$$e_s = C_1 \exp\left(\frac{A_1 t}{B_1 + t}\right) \quad [\mathrm{Pa}] \qquad (7)$$

With the constants A_1 = 17.625, B_1 = 243.04°C, C_1 = 610.94 Pa. The precision of Equation (7) is satisfactory within a temperature range of -40°C ≤ t ≤50°C, where the relative error is less than 0.4% [122]. With this information, the partial vapour pressure, e (Pa), may be determined as:

$$e = RH \cdot e_s \quad [\mathrm{Pa}] \qquad (8)$$

Hence, the humidity ratio, x ($kg_{vapour}/kg_{dry\text{-}air}$), for the prevailing conditions may be calculated by the expression:

$$x = \frac{R_{dry\ air}}{R_{vapour}} \cdot \frac{RH \cdot e_s}{(p - RH \cdot e_s)} \quad [kg_{vapour}/kg_{dry\text{-}air}] \qquad (9)$$

Where in total air pressure, p, is equal to 101,300 Pa, the gas constant for dry air, $R_{dry\text{-}air}$, is equal to 287 J/(kgK), and the gas constant for water vapour, R_{vapour}, is equal to 462 J/(kgK).

The humidity ratio is determined at inlet exhaust air and outlet exit air conditions. Any cooling of air beyond relative humidity 1.0 will result in the condensation of air vapour. However, relative humidity remains at 1.0 since the condensed water is assumed to be drained away. As a set-point value in this modelling, a lower-limit air temperature at the evaporator is set to 5°C, meaning that no further cooling of exhaust air is allowed below this value. The motivation for this is to avoid freezing on evaporator surface walls, since this temperature often is found at approximately 5°C - 10°C below that of the passing air temperature, for references see e.g. [69].

The enthalpy of moist air given per mass of dry air, h ($J/kg_{dry\text{-}air}$), may be expressed as:

$$h = c_{p,air} \cdot t_{air} + x\left(h_{fg} + c_{p,vapour} \cdot t_{air}\right) \quad [J/kg_{dry\text{-}air}] \qquad (10)$$

With specific heat capacity for air, $c_{p,air}$ (J/(kg°C)); the air temperature at the evaporator, t_{air} (°C); the evaporation enthalpy (fluid to gas) of water, h_{fg} (J/kg); and the specific heat capacity of vapour, $c_{p,vapour}$ (J/kg°C). From topic related literature, a feasible temperature range of annual average platform air temperatures has been collected, which ranges from 15°C during winter to 30°C during summer [36, 39, 93, 102, 105, 123-125], a range used for the modelling in this work. The assessed average monthly station platform temperatures and relative humidity values are specified in Table 59 in appendix 15.4.

For some references in this respect, there a several indications in the existing body of literature that platform temperatures follow ambient air temperature to a certain degree, as presented among others by [93, 102, 105]. In reference [123] it is stated that underground railway systems generate enough internal heat to increase station temperatures with as much as 8°C – 11°C above ambient temperature. Ampofo et al. [36], while summarising results presented in [124], where both an old and a modern metro station were monitored during the summer period, noticed that platform air temperatures varied between 20°C to 27°C for the modern, and between 27°C to 30°C for the old station.

Further indications are given in, for example [125], where it is stated that the natural ground temperature is around 12°C – 14°C in deep level stations (20-30 metres below surface) in the Budapest metro system. It appears, moreover, that, for stations in colder climates, the minimum winter temperature is around 15°C. Ninikas et al. [39], provides an example where, by an annual survey conducted for the Glasgow metro system, an annual average platform air temperature during winter was found at 15°C.

The expression for enthalpy in moist air may further be approximated by the following expression:

$$h \approx 1000 \cdot t_{air} + x(2500 \cdot 10^3 + 1860 \cdot t_{air}) \quad [J/kg_{dry\text{-}air}] \quad (11)$$

Between the two temperature states, prior (state 1) and after (state 2) the heat pump evaporator, the heat power balance for the heat recovery may be expressed according to:

$$\dot{Q}_L = \dot{m}_{air}(h_1 - h_2) - \dot{m}_{water} \cdot h_{water} \quad [W] \quad (12)$$

With mass flow rate of dry air, $\dot{m}_{air}$ ($kg_{dry\text{-}air}$/s), mass flow rate of condensed water, $\dot{m}_{water}$ (kg_{water}/s), and the enthalpy of water, h_{water} (J/kg).

From topic related literature, a feasible average moist air volume flow rate, $\dot{V}$ (m^3/s), of 30 m^3/s has been collected from references [37, 38, 93, 109, 113, 126] and applied uniformly in the modelling of this work. For some references in this respect, Mortada et al. [93], states that the ventilation of the London Underground is operated at full capacity each hour of the year, with high capacity ventilation shafts operated at flow rates of approximately 30 m^3/s. In reference [38], it is reported that the London Underground consists of 58 station shafts with a capacity of 10 to 60 m^3/s (average 28 m^3/s) and 55 tunnel shafts with a capacity of 12 to 90 m^3/s (average 53 m^3/s). In [126], Di Perna et al. reports an exhaust air volume flow rate of 25 m^3/s in a metro station of Barcelona, while Ampofo et al. [37] reports an average ventilation fan capacity for their investigated tunnel of 33 m^3/s.

The average moist air volume flow rate is recalculated according to Equation (13) so as to be expressed as mass flow rate of dry air:

$$\dot{m}_{air} = \frac{(p - RH_1 \cdot e_s)}{R_{air} \cdot T_1} \cdot \dot{V} \quad [kg_{dry\text{-}air}/s] \quad (13)$$

The mass flow rate of condensed water, additionally, may be determined according to:

$$\dot{m}_{water} = \dot{m}_{air}(x_1 - x_2) \quad [kg_{water}/s] \quad (14)$$

And the enthalpy of water removed from the system further:

$$h_{water} = c_{p,water} \cdot t_2 \qquad [J/kg] \qquad (15)$$

With specific heat capacity of water, $c_{p,water}$ (J/(kg°C)). In this context, the enthalpy of water removed from the system is approximated according to Equation (16):

$$h_{water} = 4190 \cdot t_2 \qquad [J/kg] \qquad (16)$$

Hereby, power capacities are feasible to be determined as monthly average values for each considered city and, on this basis, the corresponding yearly volumetric excess heat potentials may successively be assessed. For this, information on annual capacity utilisation is needed, which, in this context, has been established by an assumed 20/7 operational regime for mechanical ventilation systems uniformly for all modelled stations. This thus corresponds to a capacity factor of 83.3% (no ventilation between 01:00 and 05:00, resulting in an annual total of 7300 operational hours). This operation time is evenly distributed from January to December.

4.1.2 Spatial mapping

Albeit account for here in brief, the laborious work of georeferencing at total of 3327 public rail transportation stations throughout EU28, including several different modes, was carried out at Halmstad University during the summer of 2018. Among these stations, 2678 were eventually classified as heavy rail system stations, of which a final excerpt of 1994 underground stations qualified for the list of stations included in this modelling.

The spatial mapping itself was performed firstly by gathering official public transport maps, and other useful information sources, for each respective city metro system, see references [127-163]. Secondly, by use of e.g. Google Earth and other sources for geographical coordinates, for example [164], information on station specific latitudes and longitudes were possible to assemble in the model dataset.

4.2 Data

One significant drawback in the performed modelling is that the assessed excess heat potentials for each station has had to build on city average values, i.e. that every station in a city has been assigned the same potential. The original intention for the modelling was to be able to estimate unique potentials for each given station, but due to an unsuccessful search for appropriate data parameters, such as e.g. number of persons entering and exiting a platform on a daily, weekly, or monthly basis, or other traffic intensity indicators, this ambition could not be sustained. Instead, capacities have been established on city level, according to local climate conditions and the abovementioned conceptual assessments and distributed uniformly to all stations within each given city.

The assembled metro station dataset, thus totalling at 444 city months (37 cities and 12 annual months), includes for each city (distributed to each city station) the calculated capacities and corresponding available and accessible excess heat potentials. Despite the drawback, the model manages to incorporate local climate conditions, i.e. the temporal dimension, which influence for this source category is quite significant. As can be seen in Figure 7, where average monthly station capacities for available excess heat is presented, this influence is clearly visible.

Under the given study assumptions, in this respect mainly so the lower set-point temperature limit of exhaust ventilation air at 5°C for continued heat pump operation, significantly more latent heat is recovered in the warm summer months compared to the colder winter months. In the warmer season, station capacities are estimated to be as high as 1500 kW in some instances, while average winter season capacities are considerably lower (in the range of 400 kW per station).

Depending of course of the nature of demand to be satisfied with the recovered heat (space heating, domestic hot water, or perhaps cooling demands), this marked seasonal influence may therefore suggest two-stage heat recoveries for this source category. In such arrangements, thermal energy storages could provide proper means by which to recover the available excess heat when it is present, despite low momentary demands (as in the case of summer periods), for later use. For a corresponding graph outlining average monthly station capacities for accessible excess heat (at practical COP of 3.0), see Figure 40 in appendix 15.5.

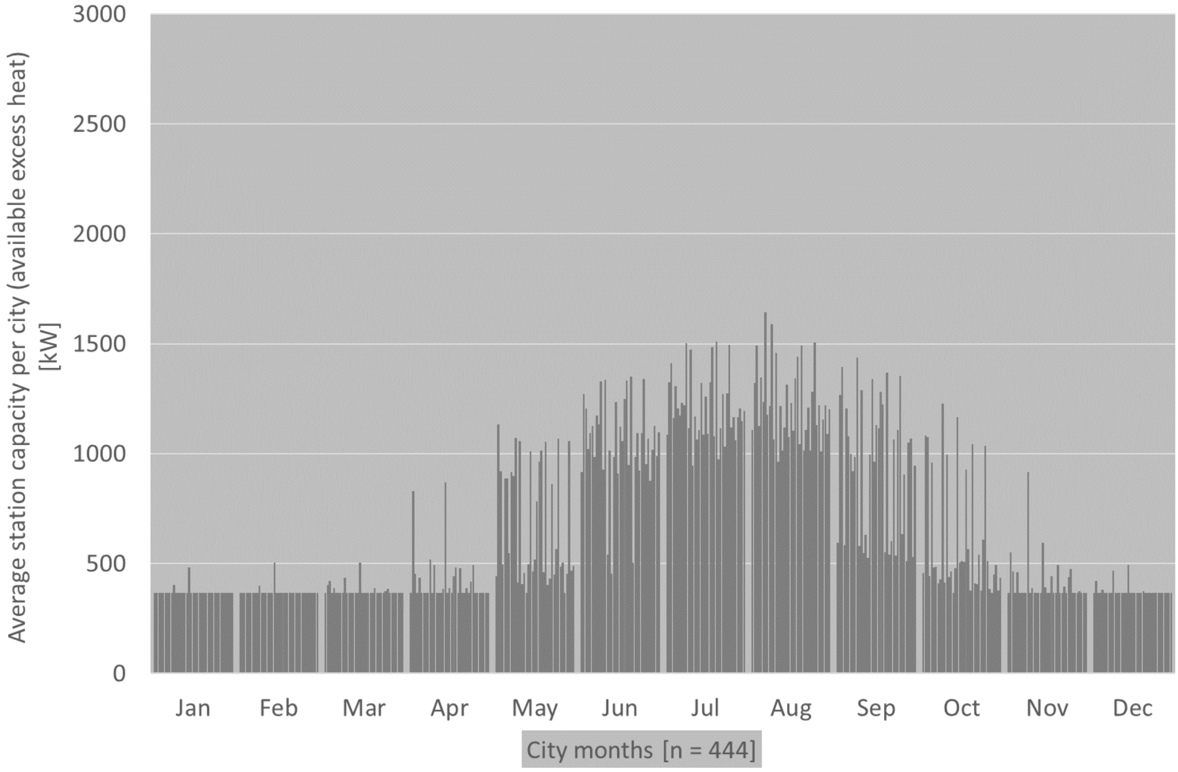

Figure 7. Average monthly station capacities per city for available excess heat (all 37 studied metro cities).

The seasonal character of metro station excess heat becomes visible also when projecting the monthly relative shares for the total contribution of available excess heat over the annual cycle, as presented in Figure 8.

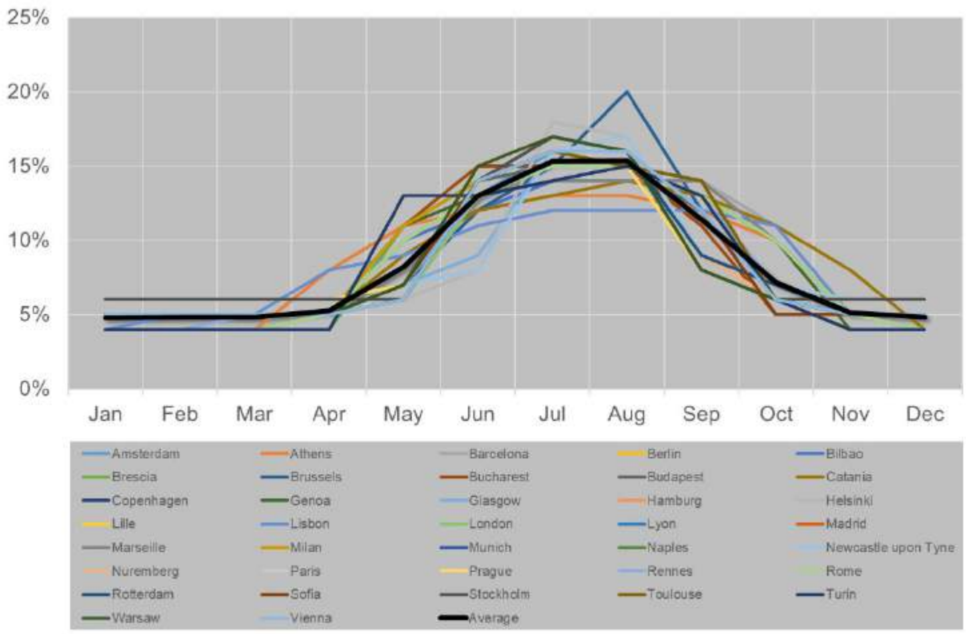

Figure 8. Temporal distribution of assessed available excess heat volumes over the annual cycle, as monthly average shares for the 37 studied cities.

4.3 Results

The total assessed available excess heat recovery potential from all considered metro stations in EU28 amounts to 35.3 PJ on an annual basis, which is detailed in Table 12 below and further illustrated in the 37 metro city map shown in Figure 9.

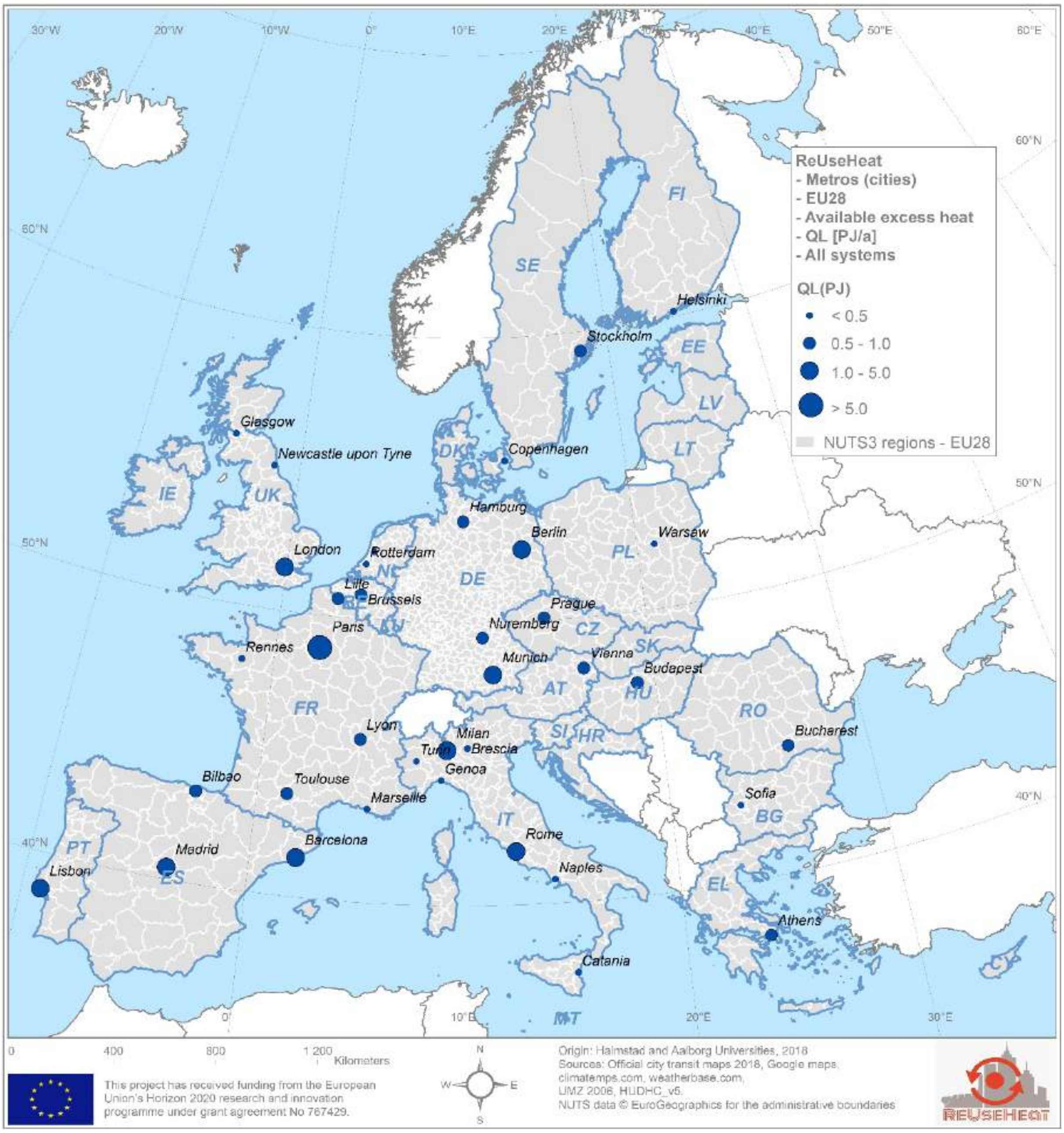

Figure 9. Available excess heat in 37 EU28 cities with metro systems in operation.

Largest available excess heat volumes are found in the cities of Paris, Madrid, and Barcelona, all with above 3 PJ as city totals, which is also visible in Figure 10. The corresponding annual city average is estimated at approximately 2 PJ per city, while the EU28 metro station average is found at some 18 TJ per station, see further Table 12 below. In view of these numbers, however, it should be kept in mind that these assessments build on the abovementioned city average level approach, why actual unique station potentials may deviate from these estimates.

In terms of numbers, France (441), Spain (407), and Germany (318), are the three member states which count most underground metro stations in all, while only a few such stations are recorded for countries like Denmark (9 stations in the Copenhagen metro system) and Finland (17).

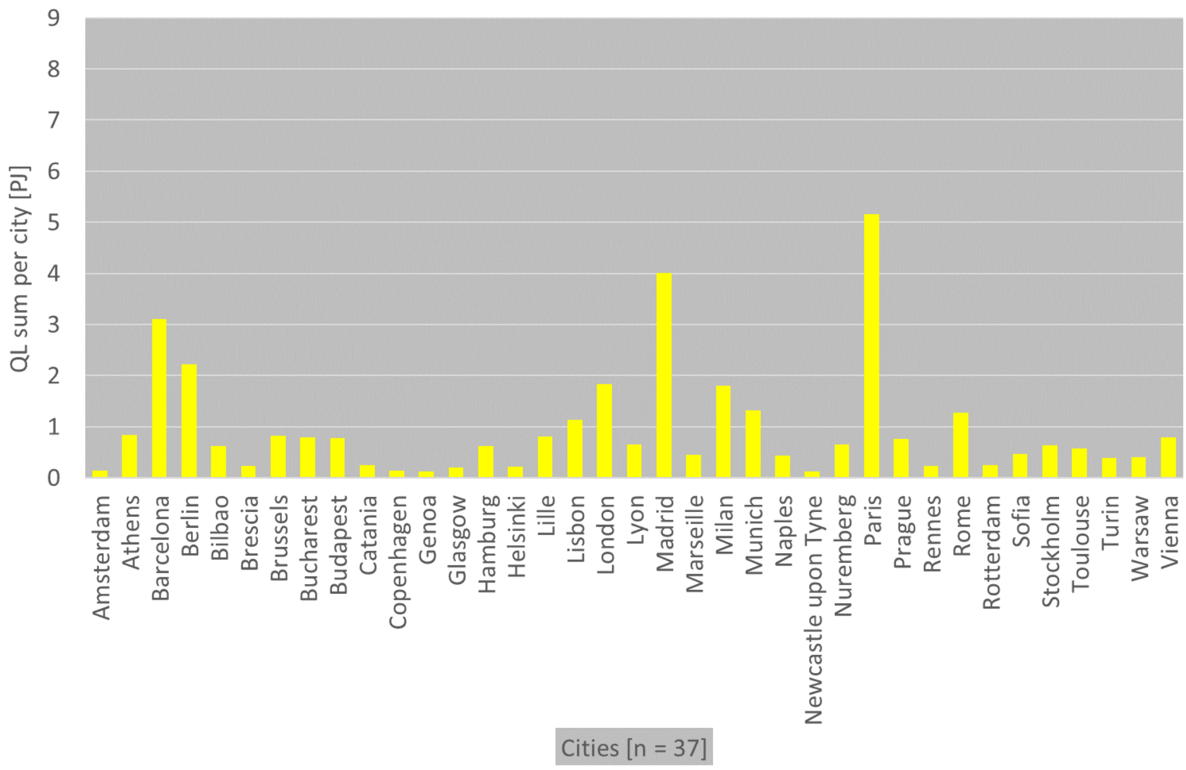

Figure 10. Summation of available excess heat per metro city (all cities).

To illustrate the high level of spatial detail maintained in this modelling, the urban metro system of the Swedish capital Stockholm is shown in Figure 11, where also the 2 kilometre buffer zone indicating an urban district heating area is visible. In this figure, the accessible excess heat potential at each station, inside or within 2 kilometres of the UMZDH-area, is depicted. As can be seen from the map, the stations in the Swedish capital are anticipated to generate in the order of 20 TJ – 25 TJ of accessible excess heat on a yearly basis, at a practical COP of 3.0, slightly below the study average at 26.6 TJ per station.

Table 12. Number of underground metro stations, available excess heat, and accessible excess heat at practical COP of 3.0. Anticipated annual average excess 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	0.8	1.2	16.6	24.9
BE	47	0.8	1.2	17.6	26.4
BG	29	0.5	0.7	16.3	24.5
CZ	53	0.8	1.1	14.3	21.5
DE	318	4.8	7.2	15.2	22.7
DK	9	0.1	0.2	14.7	22.1
EL	37	0.8	1.3	22.6	34.0
ES	407	7.8	11.6	19.0	28.6
FI	17	0.2	0.3	13.1	19.7
FR	441	7.9	11.8	17.9	26.8
HU	44	0.8	1.2	17.7	26.6
IT	214	4.5	6.8	21.1	31.6
NL	25	0.4	0.6	15.2	22.8
PL	27	0.4	0.6	14.9	22.4
PT	48	1.1	1.7	23.7	35.6
RO	45	0.8	1.2	17.6	26.4
SE	45	0.6	0.9	14.0	21.0
UK	140	2.2	3.2	15.4	23.1
Total	**1994**	**35.3**	**52.9**	**17.7**	**26.6**

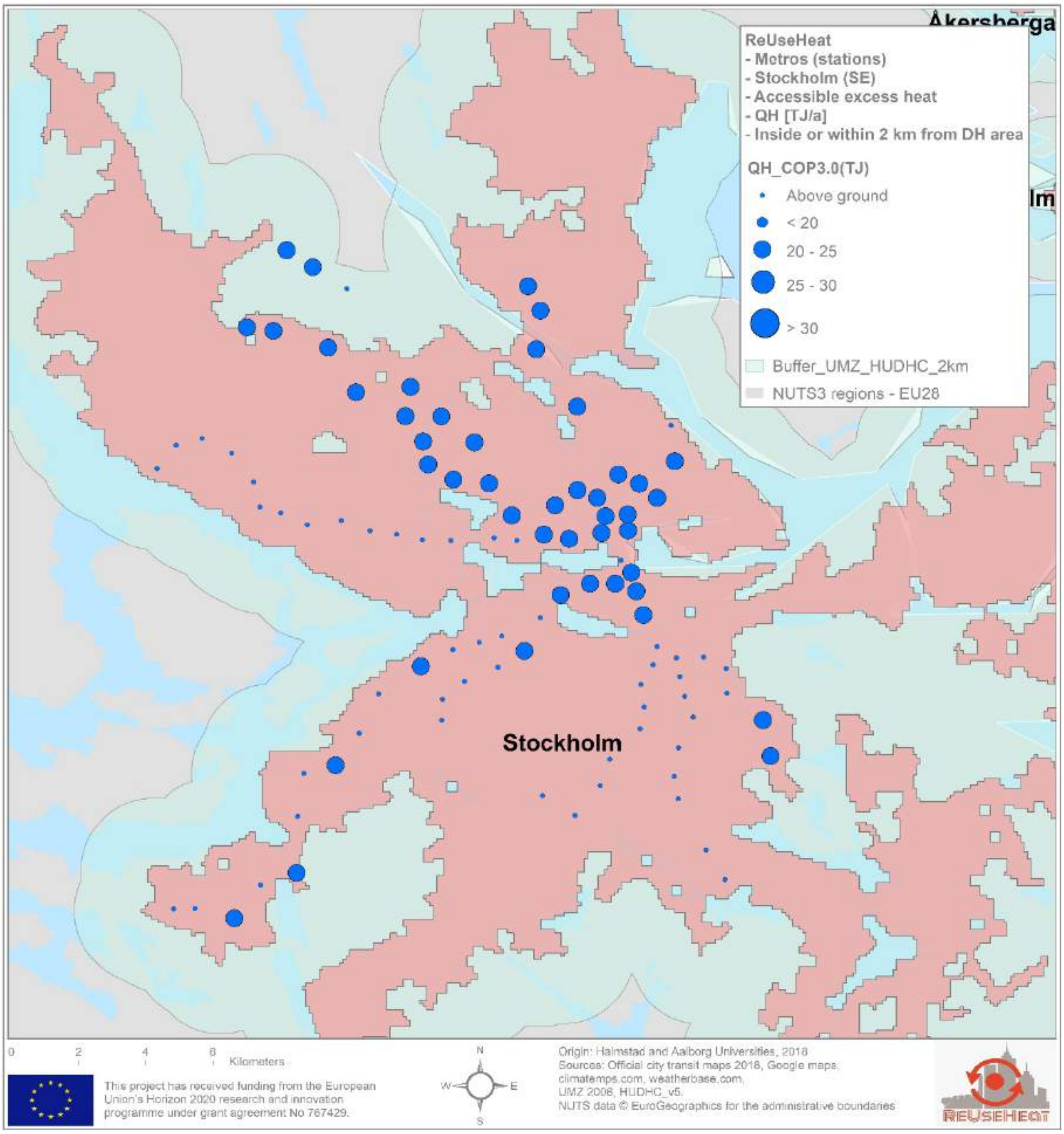

Figure 11. Accessible excess heat from metro stations at practical COP of 3.0 inside or within 2 kilometres of urban district heating areas. Close-up for Stockholm (SE).

When applying uniformly the 2 kilometre distance delimitation to all 1994 study metro stations, i.e. adjustment by the spatial dimension in consideration of local conditions, the total count of cities are reduced to 31, which in all consist of 1854 stations (see Table 13 below). The total accessible excess heat potential under these conditions, at a practical COP of 3.0, amounts to 48.6 PJ, which represents 92% of the total potential assessed for all cities.

Hereby it may be concluded, as for data centres, that a majority of EU28 metro stations are located in district heating cities, which certainly acts in favour of future large-scale excess heat recoveries from this source category. For the 31 cities with district heating systems currently in operation, a corresponding continental scope map depicting annual accessible excess heat volumes recoverable at a practical COP of 3.0 is shown in Figure 12. In this map, the prevailing opportunities in cities such as Paris, Madrid, and Barcelona are further emphasised, as well as those present in cities such as for example Berlin, Milan, London, and Munich.

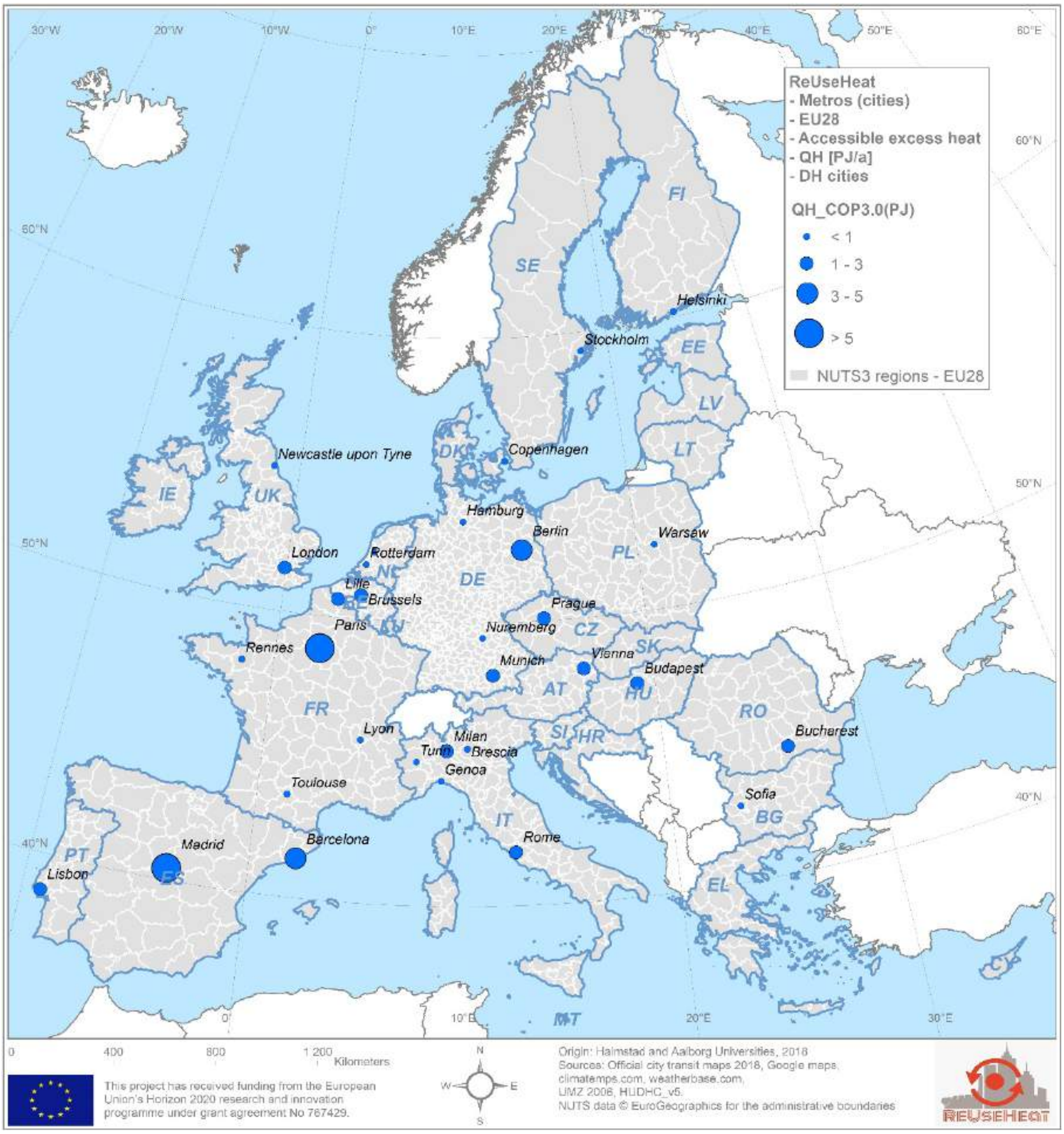

Figure 12. Accessible excess heat, at practical COP of 3.0, from 31 EU28 district heating cities with metro systems in operation.

If assuming that the excess heat from these metro stations is recovered at the low-range temperature value of 5°C, see Table 3, and further relating this to an *ad hoc* annual average supply pipe temperature of 85°C for 3rd generation district heating systems, a theoretical COP value would be found at 4.5, thus indicating an average Carnot efficiency for this source category at 67%.

Given the relatively small total volumes of recoverable excess heat that, compared to, for example, urban waste water treatment plants (as described in section 9 below), have been the result of these assessments, it is recommended to evaluate closely any real-world metro station project closely before investing. This is not to say that heat recoveries from this source category could not prove feasible, just that the margins of viable operations appear more narrow than for some other alternatives. In appendix 15.6, a complementary table with accessible excess heat volumes, inside or within 2 kilometres of urban district heating areas, at practical COP values of 2.5 and 3.5, respectively, is included for reference, see Table 60. Note also that the considered 1994 metro stations may be viewed as an operational layer in the PETA 4.3 web map [53].

Table 13. Number of underground metro stations, available excess heat, and accessible excess heat at practical COP of 3.0, inside or within 2 kilometres of urban district heating areas

MS	Metro stations [n]	QL [PJ/a]	QH COP 3.0 [PJ/a]
AT	48	0.8	1.2
BE	47	0.8	1.2
BG	29	0.5	0.7
CZ	53	0.8	1.1
DE	318	4.8	7.2
DK	9	0.1	0.2
ES	370	7.0	10.5
FI	17	0.2	0.3
FR	419	7.4	11.1
HU	44	0.8	1.2
IT	185	3.8	5.8
NL	25	0.4	0.6
PL	27	0.4	0.6
PT	48	1.1	1.7
RO	45	0.8	1.2
SE	45	0.6	0.9
UK	125	2.0	2.9
Total	**1854**	**32.4**	**48.6**

4.4 Comments

A few words on important aspects of this assessment which should be kept in mind when appreciating its findings and results. First, this study cannot guarantee the level of comprehensiveness regarding the inclusion of (all existing) individual underground stations, since the binary decision whether a given station is located above ground or underground has been made based on information collected from the Internet, and not by actual ocular inspection. In addition, further stations located underground, not included here, may exist, mainly since certain underground stations operate in public transportation modes other than that of heavy rail. Furthermore, no official European dataset, as of the number of metro systems currently in operation, has been located, why the gathered and used model data involves some uncertainty as for its completeness in terms of coverage.

To an unidentified degree, metro systems without mechanical ventilation systems exist. In such systems, the practical implementation of heat recovery applications, as assumed here, may not be feasible. Nonetheless, blast shafts located at the end of tunnels leading into station platforms, which relieve of pressures caused by the rolling stock moving through the tunnels (piston effect), appear to be present even without mechanical ventilation systems. Hence, in order to estimate heat recovery potentials, it is assumed here that stations unequipped with mechanical ventilation systems could still operate fans in the exhaust blast shafts and are therefore included in the analysis.

Two model parameters (volume flow rate and temperature) are major variables impacting on the outcome of the performed potential assessment. Changes in these parameters may correspondingly alter the assessed potentials significantly. Still, the values chosen here are well supported and synchronised with accounts given in current literature on the subject. However, in situ assessments may very well deviate from the general findings presented here, a fact which is hereby acknowledged.

5 Food production refrigeration**

Food production as industrial activity can be split into processing and preserving meat, fish, fruit and vegetables, and manufacture of oils and fats, dairy products, grain mill products, starches, bakeries, animal feeds, beverages and tobacco. These economic activities are grouped into the NACE Revision 2 Division 10, 11, and 12. However, each of these divisions can further be subdivided into specific types of food production. Each production type would have their own energy needs according to the processes each industry entails, but amongst the energy uses, this report focuses on the part related to refrigeration of manufacturing, preserving and processing of food.

The technology overview in the following is based on ref. [165]. For meat production, electricity for cooling and freezing is the largest electricity use in the sector with around 50% of the electricity consumption. Cooling/freezing is used both under the production of products and for storage of the final products. The electricity consumption is typically split, 65% cooling and freezing tunnels, and 35% cooling and freezing storage. It is the excess heat from the condenser units, related to these freezing and cooling units, that is wasted and can potentially be extracted. For fish, cooling and freezing is around 50% of the electricity use. For the dairy sector in general, 15-20% of the electricity is used for cooling and freezing processes, which is both related to production processes and storage of the final products. Typically, compression cooling units is used for this. For the beverage sector around 15% of electricity consumption is used for cooling and freezing. For bakeries, animal feed producers, and tobacco, the cooling and freezing demands are neglectable.

Theoretically, all the rejected heat from these food production refrigeration systems can be recovered. If a refrigeration system has a capacity of 300 kW and a COP of 3.0; this means that the rejected heat can be calculated as the sum of the 300-kW refrigeration capacity and the 100-kW compressor load. Thus, the rejected heat is 400 kW, or in relation to the compressor load; 400%. In practice, the COP's will vary between different types of refrigeration systems, but an average of 400% of the electricity will be used in this report, similarly to what is stipulated and estimated in [166].

5.1 Methods

Figure 13 illustrates the general methodology established for this non-conventional heat source coming from food production refrigeration systems. The methodology has been tailored according to the data gathered in order to proceed with the study aiming at an excess heat potential estimation. Here, it is important to note that given the mixed nature of the data used as starting point – geographic and non-geographic – two main outputs may be seen as a result of the methodology, both categorized as spatial and non-spatial respectively (see further section 5.3).

Our original intention was to combine data on spatially determined locations of food production facilities on an EU28 level, with specific data depending not only on the type of industry but also on the facility size, which would provide an indicator of relevancy for the excess heat contribution of the total potential. If achievable, this would principally allow a facility level bottom-up approach that would serve as a closer and less theoretical representation of the reality. However, this approach was determined unfeasible due to limited and incomplete site-specific data accessible at the moment, why the following course was taken instead.

From the methodology scheme in Figure 13, it can be seen that the process starts out with the identification of food production facilities on an EU28 scale (including geographical coordinates). In parallel, the calculation of categorized electricity consumption takes place for each category and member state respectively. This calculation comes after an extensive assessment of the facilities individual typology and use of complementary national databases introduced in order to obtain national average electricity consumption categorized by facility type and member state on a matrix format.

The process is followed by the excess heat estimation based on food production facilities electricity consumption and ends with the two outputs mentioned previously. Lastly, the spatial mapping takes place for the georeferenced output of facilities, where both the available and accessible excess heat potentials are related to current district heating areas by geospatial analysis. The latter step calculates the distances from food production facilities relative UMZDH areas by five distinctive metrics: 0 km (inside), 2 km, 5 km, 10 km, and beyond 10 km (outside).

This methodology’s four main stages can be visualized by means of different case colours as in Figure 13, and will be described in more detail in the following sections 5.1.1 to 5.1.4.

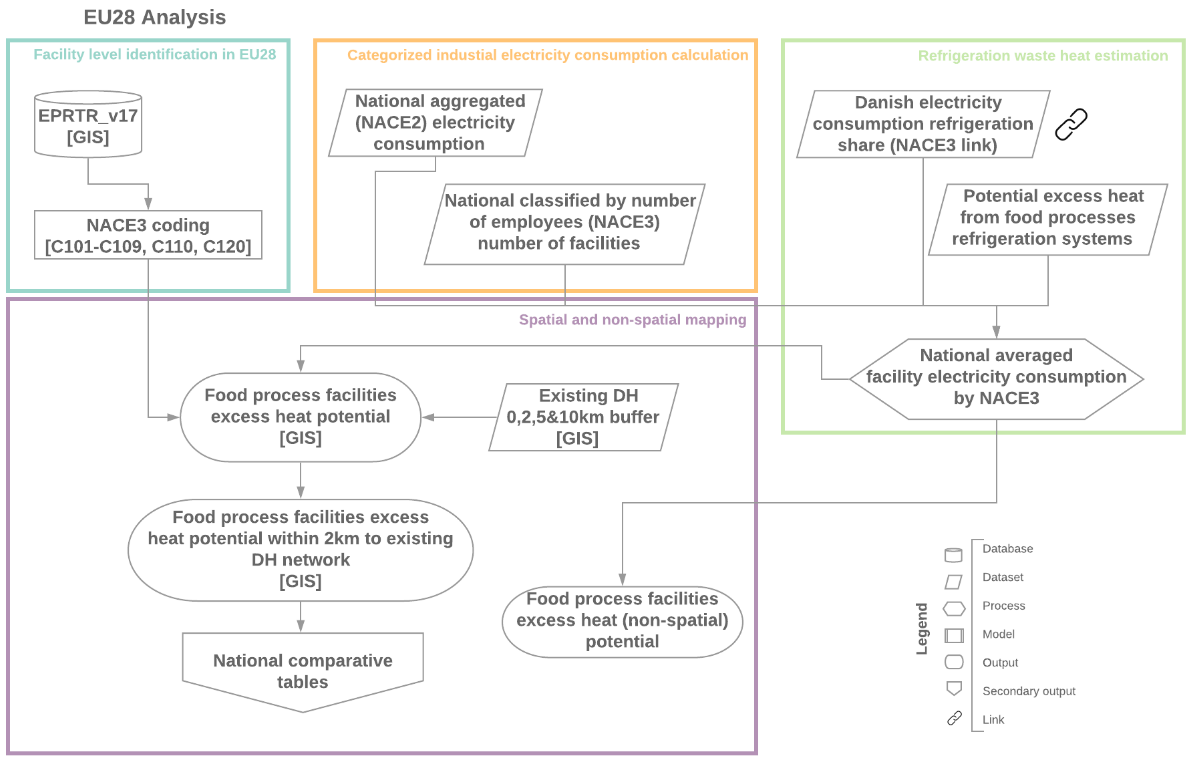

Figure 13. Food production excess heat potential methodology.

5.1.1 Identification food production facilities in EU28

For the identification of food production facilities, data on food producers at facility level was collected from the European Pollutant Release and Transfer Register (E-PRTR), hosted by the European Environmental Agency (EEA) in its Data Service [167] amongst other reporting mechanisms.

This European register is a database that includes quantitative data on key environmental pollution parameters (releases to water, air and land) from industrial facilities as pollutant issuing entities. Unique facilities are identified as point sources with their locations georeferenced with corresponding coordinates. Data is collected annually, and the version used for this study are from reporting year 2017 (published as version 17 (E-PRTR_v17)) and contains around 30,000 records of reporting facilities. Facilities have unique identification as well as reporting numbers and are classified by industrial and economic activity categories. A total of 65 industrial activities and sub-activities (IA) are included in the database, categories which are listed in the E-PRTR Directive [168]. Additionally, facilities are associated to the *Nomenclature statistique des activités économiques dans la Communauté européenne,* or European Classification of Economic Activities (NACE), published in the NACE Revision 2 and amending Directive [169], as statistical classification for economic sectors.

From the E-PRTR database, a filter was applied for the food production relevant facilities identification for this non-conventional excess heat source assessment. The selected categories are shown in Table 14. It is worth to mention that the NACE Rev.2 database classifies economic activities by division, group, and class e.g. 01, 01.1 and 01.11 respectively. For the purpose of this research, and aligned to the complementary data classification usage, the classification chosen corresponds to a NACE division and group and is termed consequently NACE2 (2 digit) and NACE3 (3 digit) as for naming convention. The latter can be visualized by the similarly coloured columns in the table.

Table 14. Food production NACE codes selection and naming convention

NACE Rev. 2		Naming convention		Description
Division	**Group**	**NACE2**	**NACE3**	
10	10.1	C10	C101	Processing and preserving of meat and production of meat products
	10.2		C102	Processing and preserving of fish, crustaceans and molluscs
	10.3		C103	Processing and preserving of fruit and vegetables
	10.4		C104	Manufacture of vegetable and animal oils and fats
	10.5		C105	Manufacture of dairy products
	10.6		C106	Manufacture of grain mill products, starches and starch products
	10.7		C107	Manufacture of bakery and farinaceous products
	10.8		C108	Manufacture of other food products
	10.9		C109	Manufacture of prepared animal feeds
11	11.0	C11	C110	Manufacture of beverages
12	12.0	C12	C120	Manufacture of tobacco products

Moreover, thresholds apply for facilities subject to report under the E-PRTR regulation, which should be noted here. These guidelines take point of departure on specified capacity thresholds per activity type – as available in Annex I: Activities, Directive No. 166/2006 [168] - and demands annual reporting along with an indication of measurement, calculation or estimation of specified pollutant releases – as available in Annex II: Pollutants, Directive No. 166/2006 – only from facilities that exceed these thresholds. For the animal and vegetable products from the food and beverage sector, the thresholds for capacity, and for main GHG (Green House Gas) emissions, can be seen in Table 15 and in Table 16 respectively.

Table 15. Directive N.166/2006 capacity threshold for the Animal and vegetable products from the food and beverage sector

Activity	Capacity threshold [tonnes/day of finished product]
8. Animal and vegetable products from the food and beverage sector	-
(a) Slaughterhouses	50
(b) Treatment and processing of animal and vegetable materials in food and drink production	-
(i) Animal raw materials (excluding milk)	75
(ii) Vegetable raw materials	300
(c) Treatment and processing of milk	200

Table 16. Directive N.166/2006 pollutant threshold for air release GHG emissions extract

Pollutant	Threshold for releases to air [kg/year]
Methane (CH_4)	100000
Carbon monoxide (CO)	500000
Carbon dioxide (CO_2)	100 million
Hydrofluorocarbons (HFCs)	100
Nitrous oxide (N_2O)	10000

Considering that only facilities exceeding the aforementioned thresholds are subject to reporting to the E-PRTR, and after performing the filtering process using the Table 14 code selection, a total of 2487 records were obtained for the whole EU28. The nationally categorized statistics of the records found can be seen in a tabular form in

Table 17. Member states Cyprus (CY) and Malta (MT) does not show available records for food production facilities reported in the E-PRTR_v17.

Table 17. Facility record statistics after E-PRTR_v17 filtering process

MS	Facilities [n]											TOTAL
	NACE3											
	C101	**C102**	**C103**	**C104**	**C105**	**C106**	**C107**	**C108**	**C109**	**C110**	**C120**	
AT	6	0	2	0	9	1	0	0	0	1	0	19
BE	41	0	17	6	15	2	1	11	8	10	0	111
BG	0	0	0	0	0	1	0	1	0	3	0	5
HR	2	0	0	1	4	0	0	5	0	4	0	16
CY	0	0	0	0	0	0	0	0	0	0	0	0
CZ	13	0	0	2	10	0	0	12	3	12	0	52
DK	12	0	0	1	12	0	0	5	0	1	0	31
EE	2	0	0	0	2	0	0	0	0	0	0	4
FI	10	0	1	0	8	0	0	2	1	2	0	24
FR	105	6	31	15	139	23	9	78	52	35	0	493
DE	86	4	9	18	89	10	9	51	7	38	0	321
EL	0	0	2	2	2	0	0	0	0	0	0	6
HU	11	0	2	5	8	2	0	1	3	4	0	36
IE	31	0	0	0	21	0	0	7	3	4	0	66
IT	31	0	26	10	38	8	21	16	19	13	2	184
LV	0	0	0	0	1	0	0	0	0	0	0	1
LT	1	0	0	0	4	1	0	2	1	0	0	9
LU	0	0	0	0	1	0	0	0	0	0	0	1
MT	0	0	0	0	0	0	0	0	0	0	0	0
NL	29	0	13	14	41	14	1	23	1	11	0	147
PL	57	4	6	6	31	1	1	36	9	15	0	166
PT	13	0	2	3	8	1	0	4	5	6	0	42
RO	11	0	0	2	2	0	0	3	1	8	0	27
SK	3	0	0	0	4	1	0	3	0	2	0	13
SI	2	0	1	0	2	0	0	0	0	3	0	8
ES	81	13	26	17	39	9	3	9	50	29	0	276
SE	12	1	3	2	15	0	0	2	0	4	0	39
UK	103	10	14	8	48	13	8	70	55	61	0	390
EU28	**662**	**38**	**155**	**112**	**553**	**87**	**53**	**341**	**218**	**266**	**2**	**2487**
(0) Zero facilities listed in database												

Given that these numbers solely correspond to facilities exceeding these thresholds (i.e. only large-scale facilities), it was considered relevant to incorporate into the analysis complementary aiding sources to proceed with the excess heat estimation. Hence, as E-PRTR is used for spatial identification (coordinates of facilities), national aggregated food production datasets were used in order to gather information on the sizing and distribution of facilities, not only on a national, but also on a categorized level. Together, these datasets enable the spatial and the non-spatial outputs referred to in the methodology illustration, Figure 13. Complementary datasets along with their usage will be introduced in the following sections.

5.1.2 Categorized industrial electricity consumption calculation

While the data introduced in Section 5.1.1 provided locations for specific facility typology, non-georeferenced European statistics from national Eurostat data were used for a deeper understanding on facility division and facility sizing for each member state. These statistics are key when talking about metrics and finding paths for enabling comparisons and diversities between countries.

The objective of this methodology process was to find an 'averaged' weighted size of food production facilities and ultimately its electricity consumption, being country and category dependent. This was done by means of specific country statistics on final electricity consumption and facility counts by number of employees, filtered by NACE Rev. 2 economic activities. In the following bulleted list, the two datasets are described:

- National aggregated (NACE2) electricity consumption: Final electricity consumption data was collected from Eurostat Energy data. Eurostat collects and publishes yearly data on supply and consumption of various fuels and electricity. Energy balances are available and diversified according to NACE Rev. 2 (NACE2) main economic division activities, which were retrieved for each EU28 member state in a MS Excel format for the year 2017 from the 2020 edition Eurostat online portal [170]. In the case of electricity consumption, the national values are aggregated for all NACE2 groups considered for food production in Table 14. Meaning that there is one aggregated national value for the electricity consumption of all NACE2 economic activities (C10, C11 and C12), namely: Manufacture of food products, Manufacture of beverages and Manufacture of tobacco products. This represents a challenge and a major drawback of the dataset since there is no classification or subdivision on electricity by NACE3. Here, it is worth mentioning that even though certain industries, such as C11 and C12, refrigeration needs are foreseen as not primary, they cannot be dismissed of the study due to this specific dataset aggregation. Irrespective, the dataset does provide an insight on the electricity consumption of the sector as a whole that will be exploited further.
- National classification by employees (NACE3) number per facility: Eurostat data on number of facilities classified by number of employees was retrieved from the Structural business statistics - business demography section for 2017 [171]. Eurostat business demography statistics present data on active population of enterprises along with various characteristics of its dynamics where the purpose is particularly to analyse small and medium-sized enterprises as Directive No. 295/2008 emphasizes [172]. Thereof, for the purpose of this research, each enterprise is considered as a physical facility where a certain economic activity takes place – in this case a NACE3 food production activity. The dataset shows facilities demography by size class and classified by NACE Rev.2 class economic activities (NACE3) for a total of 280,509 records. The facilities size class corresponds to facilities having 0-9, 10-19, 20-49, 50-249, and >250 employees respectively on each category. This means that records show number of facilities by employee range and NACE3 class category. For the EU28, a total of 280,509 facilities are found and no facilities are listed for Malta (MT) member state.

For the visualization of the two presented databases, Figure 14 and Figure 15 depict the NACE3 business demography and the final electricity consumption for the sector respectively. When comparing databases introduced in the current section, as well as in section5.1.1, it can be noticed that the number of records – facilities - of the EPRTR_v17 constute roughly onle one percentage of the ones listed in Eurostat database. Which, in one hand, emphasizes the lack of georrefereced data for enabling geospatial analysis, but, on the other hand, also translates into a potential underestimation.

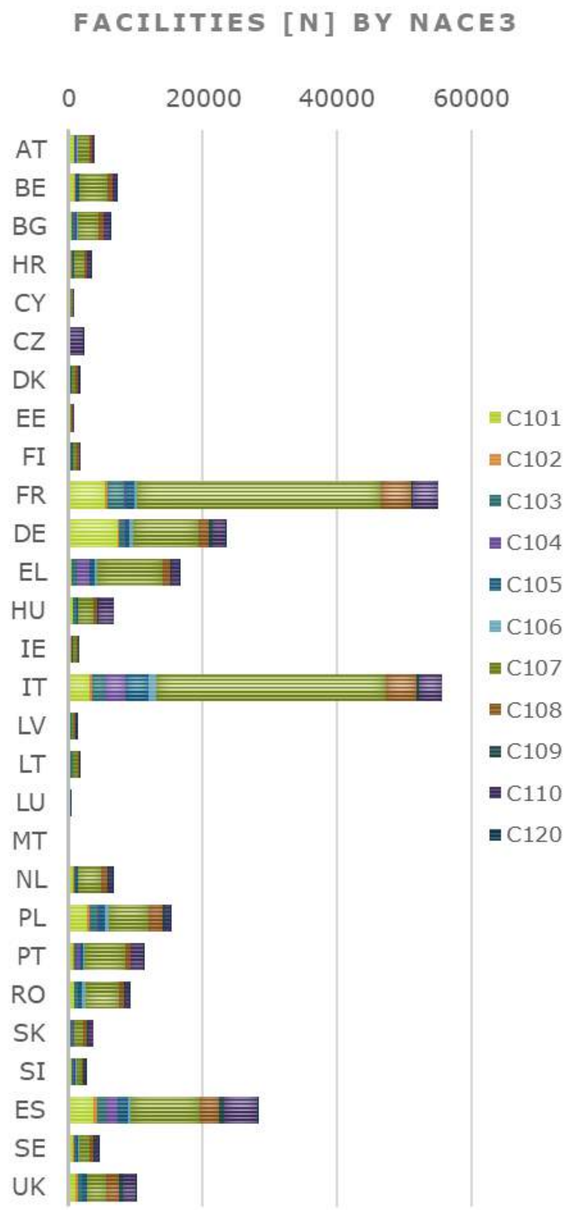

Figure 14. Eurostat number of facilities by NACE3.

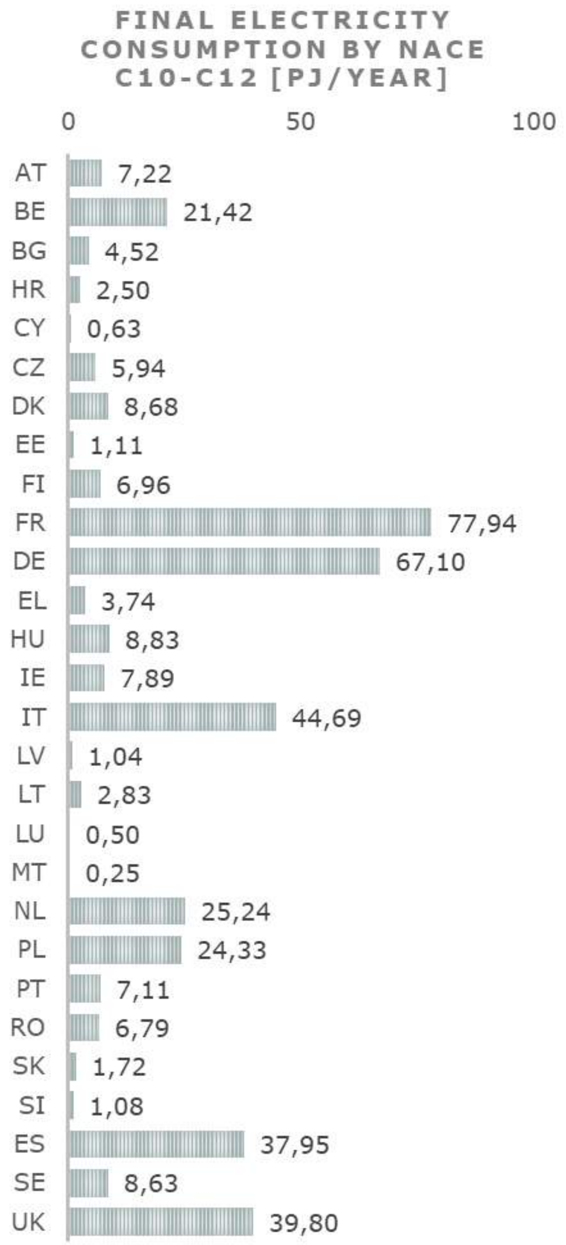

Figure 15. Aggregated NACE2 final electricity consumption.

Now, as both datasets are independent from each other, the process follows a methodology aiming at finding a link between the insights provided by Eurostat (number of facilities by employee size and final electricity consumption) and the location/typology provided by the facility register E-PRTR.

This link bases its assumptions on weighted factors which allows to nationally identify, the averaged facility sizes along with its final electricity consumption. For a better understanding of this sub-process, an example on the final electricity consumption estimation for a Danish facility type C101, see Table 18, is described in the following lines and exemplified in Figure 16. The calculations of the mentioned example can be seen also in Figure 42 in Appendix 15.7, jointly with the number sequence (1-5) of the process shown in Figure 16.

Table 18. Danish industry sector factor for weighted electricity intensity. Source: [165]

NACE3	Danish industry branch	Facilities [n]	Total electricity consumption [TJ/year]	Electricity consumption per facility [TJ/facility]	Electricity intensity branch factor
C101	Slaughtering	89	1336	15.01	0.68
C102	Fish processing	65	303	4.66	0.21
C103	Other food products	38	127	3.34	0.15
C104	Other food products	304	1136	3.74	0.17
C105	Dairy	67	1479	22.07	1.00
C106	Other food products	304	1136	3.74	0.17
C107	Bakery	90	332	3.69	0.17
C108	Other food products	86	556	6.47	0.29
C109	Animal feeds	56	764	13.64	0.62
C110	Beverage	38	542	14.26	0.65
C120	Tobacco	7	30	4.29	0.19

The process starts out with the *facility size* and *sizing factor* given as input, along with the *electricity intensity branch factor*. The last factor is derived from the weighting of data published on the Danish companies survey of energy consumption [165] and it was used here to identify NACE3 classes electricity intensity, taking dairy industry branch as index, as seen in Table 18. It is worth mentioning that this process provides a hint on the electricity consumption of various food production related activities but fails to provide any information of sizing facility differentiation amongst the different NACE3 categories.

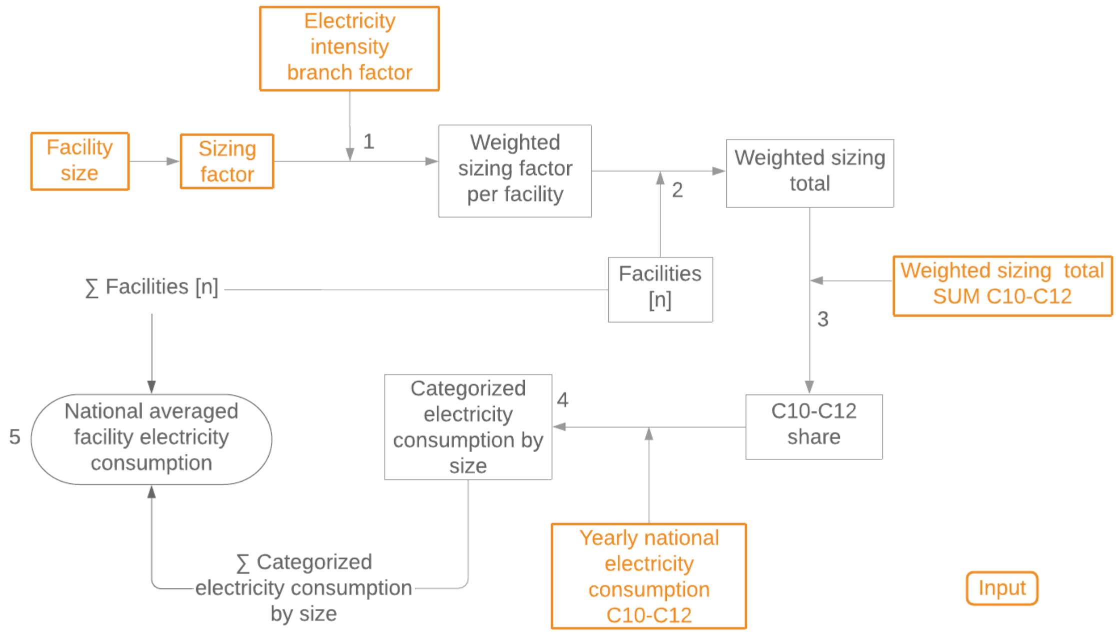

Figure 16. Final electricity consumption estimation process for a Danish facility type C101.

The factors multiply generating a *weighted sizing factor per facility* as individual factor (1), which in turn multiplies with the number of *facilities [n]* (2) to create a *weighted sizing total* for all facilities pertained to that same size. Each of these subtotals on the whole database are added in order to have a *weighted sizing total SUM C10*-C12, which allows a *C10-C12 share* calculation for every size category (3). Later, the share uses the *yearly national electricity consumption C10-C12* to compute a weighted *categorized electricity consumption by size* (4), which summed as a sectorial subtotal, divides the *facilities [n] subtotal* to then produce a *national averaged facility electricity consumption* (5). This process was made for each EU28 member state and NACE3 category size facility record and the final output is presented in section 5.2, Table 20.

5.1.3 Refrigeration excess heat estimation

Once the electricity consumption at facility level is estimated, the next coloured box in the methodology of Figure 13 indicates the estimation of refrigeration processes excess heat. For this purpose, it was necessary to first identify each of the share of electricity that is used for refrigeration processes by the different food production industries, depending on specific needs.

The already introduced Danish study survey on different industries energy consumption was used by means of linking NACE3 industry sector and Branch number [165]. The individual industry branches fact sheets on their respective detailed energy consumption were carefully assessed and the different shares of refrigeration - Table 19 - were obtained. The branch labelled "Other food products" was concluded to be suitable and assigned to different fruit, vegetable and grain products after an examination of their industry processes due to differences between NACE and branch classifications.

Table 19. Final electricity consumption refrigeration share by NACE3

NACE3	Description	Branch	Description	FC_{EL} refrigeration share [%]
C101	Processing and preserving of meat and production of meat products	7	Slaughtering	42%
C102	Processing and preserving of fish, crustaceans and molluscs	8	Fish processing	37%
C103	Processing and preserving of fruit and vegetables	13	Other food products	27%
C104	Manufacture of vegetable and animal oils and fats	13	Other food products	27%
C105	Manufacture of dairy products	9	Dairy	23%
C106	Manufacture of grain mill products, starches and starch products	13	Other food products	27%
C107	Manufacture of bakery and farinaceous products	10	Bakery	10%
C108	Manufacture of other food products	13	Other food products	27%
C109	Manufacture of prepared animal feeds	11	Animal feeds	0%
C110	Manufacture of beverages	14	Beverage	15%
C120	Manufacture of tobacco products	15	Tobacco	0%
(FC_{EL}) Final electricity consumption				

Followingly, for the available excess heat calculations in this study, 100% of the heat available at the condensers in the modelled refrigeration system is here used. The temperatures of this excess heat range from 20 to 40 °C [166] and represent 400% of the electricity consumption used for refrigeration purposes, which is therefore translated into the available excess heat potential (Q_L) in this report.

5.1.4 Spatial and non-spatial mapping

In this step of the methodology, the final electricity consumption (FC_{EL}) along with its respective refrigeration share, and the associated excess heat potentials (Q_L), are joined with the spatial data from E-PRTR in order to develop a facility level map of the excess heat potential in all of EU28.

This georeferenced potential is then used together with geographical data of existing DH infrastructure to estimate how much of the potential is found within 0 km, 2 km, 5 km, 10 km, and beyond 10 km, of current district heating areas, as seen in the methodology shown in Figure 13. Altogether, this process represents the spatial mapping part of the methodology. Additionally, a non-spatial excess heat potential is calculated using the Eurostat dataset. Both of the outputs from the methodology use the matrix presented in section 5.2, Table 20.

5.2 Data

This section presents the output reached by the methodology described in section 5.1.2 which serves as the primary input data for the spatial and non-spatial heat recovery potential calculation explained in section 5.1.4. The matrix developed is shown in Table 20 and portrays the nation dependent, average, facility level final yearly electricity consumption.

All of the facilities identified, both those georeferenced in E-PRTR_v17 dataset and those non-georeferenced as in Eurostat dataset, were assigned values from this matrix to later compute the final electricity consumption refrigeration share (FC_{EL} refrigeration share [%], as presented in Table 19) and the available excess heat potential (Q_L) at facility level.

Table 20. Averaged facility and NACE3 level final yearly electricity consumption

MS	FC_{EL} [TJ/year]										
	NACE3										
	C101	C102	C103	C104	C105	C106	C107	C108	C109	C110	C120
AT	3.16	1.27	0.71	0.64	5.17	0.76	0.79	1.81	3.46	2.67	0.00
BE	7.08	2.29	2.97	5.53	8.12	2.63	1.15	3.18	12.56	5.59	1.85
BG	2.26	0.53	0.25	0.30	2.97	0.33	0.26	0.54	1.04	1.11	0.92
HR	1.80	0.79	0.32	0.27	2.69	0.35	0.37	0.73	1.21	1.18	2.14
CY	2.04	0.00	0.44	0.22	2.46	0.22	0.32	0.99	0.98	0.96	0.00
CZ	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.65	2.27
DK	15.14	4.89	2.22	2.92	15.23	4.58	2.66	3.38	12.18	6.77	3.64
EE	3.51	1.03	0.46	0.38	6.28	0.52	0.62	0.99	1.87	2.15	0.00
FI	7.76	1.74	1.69	1.62	18.03	1.90	1.68	3.83	6.91	7.66	0.00
FR	3.73	1.74	0.81	0.87	6.57	1.14	0.67	1.62	6.04	3.19	0.00
DE	4.28	0.83	1.31	0.60	9.19	0.97	1.25	2.62	5.38	4.47	8.37
EL	0.88	0.24	0.19	0.11	0.95	0.12	0.12	0.26	0.49	0.52	0.60
HU	3.50	0.38	0.49	0.45	5.39	0.57	0.56	0.91	2.83	1.47	0.00
IE	12.97	2.07	1.03	0.90	14.82	0.90	1.55	7.20	10.38	0.00	0.00
IT	2.37	0.61	0.57	0.34	3.09	0.40	0.36	0.85	1.98	1.96	0.00
LV	1.78	0.62	0.24	0.30	3.35	0.40	0.31	0.52	1.17	1.22	0.23
LT	3.96	1.62	0.41	0.53	15.00	1.13	0.71	1.42	4.47	4.18	6.72
LU	7.62	0.00	1.24	0.00	10.93	2.08	1.23	1.31	0.00	4.08	8.49
MT	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NL	8.58	2.76	2.91	3.66	13.55	2.22	1.56	3.68	10.50	5.22	5.70
PL	3.39	1.24	0.69	0.50	5.30	0.63	0.60	1.09	2.39	2.67	1.34
PT	1.91	0.90	0.31	0.24	2.03	0.36	0.27	0.58	2.29	1.09	1.35
RO	2.31	0.82	0.24	0.37	2.41	0.29	0.33	0.62	1.34	1.42	1.56
SK	0.74	0.00	0.13	0.17	1.70	0.86	0.23	0.33	0.56	0.71	0.00
SI	0.94	0.41	0.14	0.15	1.04	0.15	0.18	0.32	1.32	0.68	0.16
ES	2.87	1.21	0.72	0.46	3.33	0.66	0.45	1.13	2.61	1.89	0.42
SE	4.29	1.10	0.75	1.03	5.07	0.97	0.84	1.58	3.05	2.71	2.27
UK	9.44	2.88	1.67	1.45	9.84	1.96	1.65	3.13	7.30	3.65	0.88

5.3 Results

The developed top-down methodology allows an estimation of the heat recovery potential from facilities involved in food production industrial activities, a potential which is presented in the following. The facility level matrix for available excess heat conceived as referential for each of the NACE3 categories is attached below in Table 21. Here, the chosen output of averaged facility level potential must be seen in light of missing information on site specifics. It is important to note that a consideration of real facility sizes, for which no data was available for the current study, likely would lead to significant variations of the results shown in Table 21 and, therefore, the numbers displayed should be considered as indicative only.

Table 21. Average available excess heat at facility level by NACE3 classes and EU28 Member States

MS	QL [TJ/year] facility level										
	NACE3										
	C101	C102	C103	C104	C105	C106	C107	C108	C109	C110	C120
AT	5.311	1.880	0.769	0.690	4.838	0.826	0.315	1.951	0.013	1.604	0.000
BE	11.893	3.397	3.207	5.977	7.592	2.838	0.459	3.434	0.047	3.352	0.000
BG	3.800	0.789	0.273	0.327	2.774	0.361	0.105	0.584	0.004	0.668	0.000
HR	3.027	1.175	0.344	0.287	2.513	0.380	0.146	0.786	0.004	0.708	0.000
CY	3.435	0.000	0.480	0.238	2.296	0.238	0.127	1.068	0.004	0.576	0.000
CZ	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.591	0.000
DK	25.442	7.252	2.401	3.157	14.237	4.942	1.066	3.652	0.045	4.061	0.000
EE	5.893	1.523	0.496	0.410	5.874	0.563	0.248	1.072	0.007	1.291	0.000
FI	13.036	2.584	1.827	1.745	16.858	2.049	0.673	4.137	0.026	4.593	0.000
FR	6.264	2.583	0.872	0.936	6.147	1.233	0.268	1.747	0.022	1.911	0.000
DE	7.187	1.229	1.418	0.649	8.594	1.044	0.501	2.834	0.020	2.685	0.000
EL	1.476	0.362	0.201	0.115	0.892	0.133	0.049	0.281	0.002	0.309	0.000
HU	5.878	0.567	0.527	0.489	5.042	0.612	0.226	0.987	0.010	0.883	0.000
IE	21.794	3.071	1.117	0.974	13.854	0.974	0.618	7.776	0.039	0.000	0.000
IT	3.987	0.909	0.614	0.368	2.890	0.434	0.145	0.920	0.007	1.173	0.000
LV	2.984	0.918	0.260	0.323	3.128	0.431	0.125	0.567	0.004	0.732	0.000
LT	6.646	2.403	0.438	0.571	14.022	1.222	0.282	1.529	0.017	2.505	0.000
LU	12.798	0.000	1.340	0.000	10.218	2.248	0.490	1.420	0.000	2.449	0.000
MT	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
NL	14.410	4.093	3.145	3.954	12.666	2.403	0.623	3.971	0.039	3.132	0.000
PL	5.700	1.838	0.741	0.545	4.952	0.686	0.242	1.175	0.009	1.601	0.000
PT	3.215	1.333	0.340	0.255	1.898	0.385	0.109	0.624	0.009	0.655	0.000
RO	3.882	1.210	0.257	0.402	2.256	0.318	0.132	0.665	0.005	0.851	0.000
SK	1.238	0.000	0.140	0.181	1.585	0.925	0.093	0.353	0.002	0.428	0.000
SI	1.587	0.605	0.155	0.164	0.977	0.162	0.071	0.342	0.005	0.407	0.000
ES	4.816	1.793	0.779	0.496	3.111	0.711	0.182	1.219	0.010	1.133	0.000
SE	7.204	1.634	0.812	1.111	4.741	1.051	0.335	1.708	0.011	1.627	0.000
UK	15.852	4.271	1.807	1.569	9.204	2.121	0.659	3.379	0.027	2.188	0.000

Additionally, national aggregated results are presented hereby in two separate tables, one for the spatially identified potential using georeferenced data and another to the statistical non-georeferenced dataset. Table 22 outlines both available and accessible annual excess heat volumes (at COP of 3.0) estimated spatially for all 2487 facilities, whilst Table 23 portrays the same parameters for a total of 280,509 facilities.

When comparing both output potentials, this difference becomes relevant since the number of facilities used for the spatial potential results in roughly only 1% of the non-spatial potential. Available excess heat (Q_L), and accessible excess heat (Q_H) is here presented for the case of a practical COP of 3.0. Additional available excess heat potentials have been calculated and are displayed in Table 61 in Appendix 15.8.

Table 22. Spatial heat recovery potential

MS	Facilities [n]	QL [PJ]	QH COP3.0 [PJ]
AT	19	0.08	0.12
BE	111	0.77	1.15
BG	5	0.00	0.00
HR	16	0.02	0.03
CY	0	0	0
CZ	52	0.02	0.03
DK	31	0.50	0.75
EE	4	0.02	0.04
FI	24	0.28	0.43
FR	493	1.80	2.71
DE	321	1.67	2.51
EL	6	0.00	0.00
HU	36	0.11	0.17
IE	66	1.02	1.53
IT	184	0.29	0.43
LV	1	0.00	0.00
LT	9	0.07	0.10
LU	1	0.01	0.02
MT	0	0	0
NL	147	1.19	1.79
PL	166	0.56	0.84
PT	42	0.07	0.10
RO	27	0.06	0.09
SK	13	0.01	0.02
SI	8	0.01	0.01
ES	276	0.61	0.92
SE	39	0.17	0.26
UK	390	2.56	3.84
EU28	**2,487**	**11.93**	**17.90**

Table 23. Non-spatial heat recovery potential

MS	Facilities [n]	QL [PJ]	QH COP3.0 [PJ]
AT	3,959	7.76	11.64
BE	7,122	21.43	32.14
BG	6,159	4.33	6.50
HR	3,253	2.30	3.45
CY	771	0.58	0.87
CZ	2,243	3.56	5.34
DK	1,644	8.57	12.85
EE	737	1.15	1.73
FI	1,749	6.84	10.26
FR	55,144	72.03	108.04
DE	23,451	76.78	115.16
EL	16,420	3.00	4.50
HU	6,762	8.09	12.14
IE	1,348	9.54	14.31
IT	55,655	39.33	59.00
LV	1,196	1.11	1.67
LT	1,627	3.01	4.52
LU	158	0.48	0.73
MT	0	0	0
NL	6,629	23.88	35.82
PL	15,202	27.44	41.16
PT	11,218	6.14	9.20
RO	9,143	6.60	9.90
SK	3,720	1.46	2.19
SI	2,481	1.15	1.73
ES	28,248	38.07	57.11
SE	4,488	8.81	13.21
UK	9,982	39.76	59.63
EU28	**280,509**	**423.21**	**634.81**

The geographically assessed available excess heat recovery potential from all considered food production facilities is illustrated in Figure 17. A noticeable potential is seen in the Member States United Kingdom (UK), France (FR), and Germany (DE). These countries alone account for half of the EU28 total potential (9.1 PJ) due to amongst others, the number of meat product and dairy related production facilities identified.

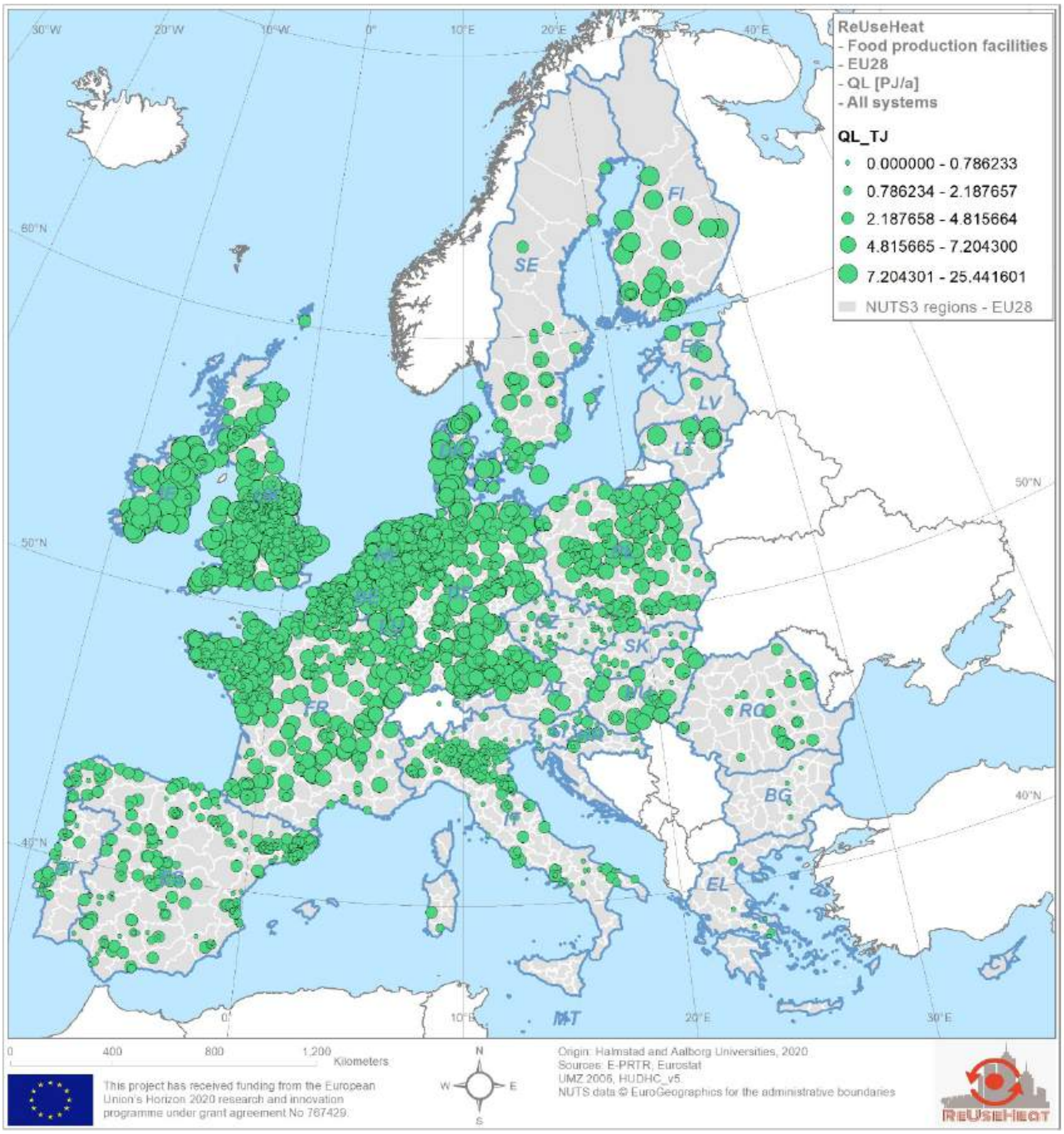

Figure 17. Available excess heat potential for 2487 geo-referenced food production facilities identified in EU28.

For this set of spatially determined food productions facilities, i.e. the 2487 georeferenced facilities displayed in Figure 17, the pre-defined distances relative UMZDH areas was applied uniformly (note the exclusion of Greece in this step, as explained above in section 2.3.1), indicating whether a given facility is located within (inside), within 2 kilometres, within 5 kilometres, within 10 kilometres, or beyond 10 kilometres (outside), of these areas.

At the default setting of inside or within 2 kilometres of UMZDH areas, the total count of facilities is narrowed down to 699 facilities, as presented Table 24. The total count of members states which host food production facilities reporting under the EPRTR regulation, is reduced from 26 at the unrestricted setting (no facilities reporting in Cyprus or Malta), to 23 member states at the default setting, which is reflected in a reduction of the available excess heat potential from 11.9 PJ per year to 3.2 PJ per year. At a practical COP of 3.0, the corresponding accessible excess heat potential is similarly reduced from 17.9 PJ per year to some 4.8 PJ per year. Corresponding tables outlining the output at practical COP values of 2.5 and 3.5 are presented in Table 62 in Appendix 15.8.

Table 24. Available and accessible excess heat from georeferenced food production facilities at default setting of inside or within 2 kilometres of current urban district heating areas (UMZDH areas). Accessible excess heat at practical COP of 3.0

MS	Facilities [n]	QL [PJ]	QH COP3.0 [PJ]
AT	14	0.05	0.08
BE	68	0.43	0.65
CZ	31	0.01	0.02
DE	77	0.33	0.50
DK	23	0.35	0.53
EE	3	0.02	0.03
ES	21	0.05	0.08
FI	19	0.23	0.35
FR	92	0.34	0.52
HR	10	0.02	0.02
HU	24	0.10	0.16
IE	5	0.03	0.04
IT	25	0.04	0.06
LT	3	0.02	0.03
LV	1	0.00	0.00
NL	32	0.17	0.25
PL	91	0.31	0.47
PT	4	0.00	0.00
RO	13	0.02	0.04
SE	28	0.12	0.18
SI	5	0.01	0.01
SK	12	0.01	0.02
UK	98	0.49	0.74
EU28	**699**	**3.18**	**4.78**

5.4 Comments

Compared to other studies on the estimation of excess heat from industrial processes, where the food industry is assessed as a whole, single category, this study tries to provide a deeper level of analysis on the different refrigeration needs of classified food production. The commonly used generalization clusters food, beverages and tobacco industry together, not providing the necessary insight for the unique and diverse industry processes involved and therefore neither for its refrigeration specifics.

A large part of the work done for this study was to find paths to geographically identify the categorized facilities, but unfortunately data availability and accessibility was limited to what the E-PRTR database could offer. The database only includes facilities that exceed the stated threshold limits, leaving facilities that indeed perform refrigeration processes below the threshold limits unaddressed. Furthermore, initially, the plan was to use the GHG emissions information from E-PRTR as indicator of the excess heat potential, but the focus of 'refrigeration only' was challenged against a totalized emission from all processes related to a certain facility. Thus, the only information that was used from E-PRTR database, was the location and the NACE classification. It is due to this georeferenced limitation that the methodology included statistical datasets such as those used from Eurostat.

Contrary to the limited facilities in the E-PRTR database, Eurostat indeed enlists all the facilities registered as businesses under a given economic activity and, although location data is not included, provides a grasp of the industry demographics and its electricity consumption by country. From the start, the vast difference in number of facilities in each dataset was clear, which exposes the necessity for enhancing the collection and accessibility for spatial data concerning the food production sector in the future. This, since – according to the outputs of this report - a major excess heat potential coming from food production facilities is not possible to spatially determine as by the facility level. It may be remarked that any potential assessment, like the one presented here, would benefit from increased access of georeferenced data, which would promote higher degree of spatial analytics and aid research activities in order to have a closer representation of reality.

While focusing in refrigeration systems, the methodology ignores other, in many cases relevant, sources of excess heat coming from these industries, such as exhaust gases from dryers/furnaces, steam or gas boilers in the dairy industry. Therefore, the excess heat potential shown in this report should be interpreted as indicative values for what is believed to be a greater potential when more heat sources are considered in the food production industry. Furthermore, the electricity intensity index and the derived refrigeration share used in the methodology, are based on available Danish industry technologies from 2012. The values of industry electricity intensity and refrigeration share will vary from country to country according to the technology and local factors related to these refrigeration systems.

Finally, the methodology used in this report does not consider the temporal distribution of the output potential excess heat, nor as to its use, although the literature review revealed rather constant production conditions for facilities in the food production industries.

6 Food retail refrigeration**

Food retail is part of NACE classification 47.2: retail sale of food, beverages, and tobacco in specialised stores [169]. The potentials for heat recovery coming from food retail is derived from systems for perishable food that needs refrigeration as preservation measure. This refrigeration is continuous for refrigerated storage areas and display cases, which makes food retail stores an attractive provider of waste heat.

The energy usage breakdown for food retail stores is highly case dependent. From literature and different case studies, food retail stores use between 35-50% of its total electricity consumption for refrigeration, 15-25% for lighting and display, and 10-20% for space heat demand [173-176]. In the UK, the total energy consumption of a typical food retail store is between 700-1000 kWh/m^2 [175] whereas in Denmark, Sweden and The Netherlands, food retail stores are categorized as energy efficient when their total energy consumption is below 400 kWh/m^2. This for an average total area of 1360 m^2 and 73 opening hours per week [177]. This threshold varies significantly in other parts of the world e.g. USA and Canada, where opening hours are massively extended as well as larger store sizes.

For this research, data found in literature to be relevant for food retail store identification, classification and excess heat assessment was processed. European experiences state that energy consumption in food retail stores decreases with increasing store area and decreases with extended opening hours. The latter on a basis of ca. 1 % for each 100 m^2 and 0.5 % per additional – weekly - opening hour [177]. Hence, both indicators of area and opening hours are used in this investigation and will be further explained in section 6.1.

Within the food retail sector, various types of systems used for commercial refrigeration are used; however, during the past years a rapid evolution towards environmental and efficient strategies is noticeable. Specific efforts are put within the sector's technology and its main stakeholders' collaboration due to its significance in energy intensive buildings within the commercial sector, as the IEA in [178] emphasizes. Additionally, refrigerant usage and leakage poses an environmental challenge of the current technology by itself. Key indicators for the assessment of these strategies rely on measurability on refrigerant charge, yearly leakage rate, energy efficiency and regional energy conversion factors (CO_2/kWh). This, taking the Total Equivalent Warming Impact (TEWI) as an example for global warming contributing indicator, is especially sensible to energy performance of a system as concluded when comparing the different metrics [179].

This new trend within the refrigeration systems focuses on minimizing refrigerant charge and leakage, with an overall shift from Chlorofluorocarbon (CFC) and Hydrochlorofluorocarbon (HCFC) type of refrigerants to more environmentally friendly, meaning lower GWP (Global Warming Potential) types. In the EU, HFCs are currently on a phase-down stage, starting in 2015 and ending with a 79% cut-down in 2030 [180]. This phase-out is triggered in the EU primarily by the fluorinated greenhouse gases and repealing regulation - F-gas Regulation - from the European Commission of 2014 [181], which bans refrigerants with 1500 and above GWP index, but also following main global regulations such as The Kigali update to the Montreal protocol – ratified by the EU in September 2018 [182], and the United States Significant New Alternatives Policy (US SNAP) for refrigeration and air conditioning. These transitions have a direct effect on retail stores refrigeration systems and require them to shift to new technologies. Seeking to reduce the harmful environmental effects from refrigerants, common HFCs are alternatively replaced by CO_2, which in exchange provides a significant reduction on the GWP index (from 3900 to 1) [183] with data from [181].

The state-of-the-art and latest development using this refrigerant is the CO_2 trans-critical booster, which provides cooling in the medium temperature (MT) cabinets and low temperature (LT) freezers [184], where these capabilities are incorporated in a single compact unit where LT compressors serve as a booster to the MT ones. The system is familiar and uses the same components as the traditional Direct Expansion (DX) system i.e. compressors, evaporators, condensers and expansion valves. The difference relies on the CO_2 refrigerant operation since it requires higher pressures, dependent on ambient conditions [185]. Regarding heat recovery, CO_2 trans-critical booster systems reach a high temperature at the compressor discharge, allowing heat recovery at various temperature levels e.g. domestic hot water (70-50°C) or direct space heating (50-40°C) [186].

For this research, CO_2 trans-critical booster is deemed as the available technology for all food retail stores within Europe. This, since it has been experienced already in the Northern European countries and has shown particularly efficient for recovering heat to cover demands within the facilities, such as for space heating, with an average heat recovery Coefficient of Performance (COP) of 4.5 [187]. At first, this efficiency was related to cold climates, however, in [188] researchers suggest that CO_2 integrated cascade systems are an efficient solution able to provide thermal demands in retail stores both in cold and warm climates. This when considering certain modifications to the standard CO_2 system e.g. ejectors, parallel compression, flooded evaporation, amongst others.

According to Shecco, publisher and editor of Accelerate Magazine, Europe is the world leader in trans-critical CO_2 systems with 23,000 installations as of the beginning of 2020 [189]. Outstanding retail leaders in Europe switching and adopting CO_2 systems are the Schwarz group, Sainsbury's, Carrefour S.A., METRO AG and Ahold Delhaize. As of 2017, Carrefour has ca. 380 stores operating with natural refrigerants using CO_2 systems whilst German Aldi has 1,496 stores. Swiss Migros and UK Sainsbury have 451 and 274, respectively [190]. Overall, within the food retail industry, 90% of medium to large European food retailers are operating with CO_2 systems, whereas smaller stores named convenience stores are switching to hydrocarbons refrigerants. Therefore, the technology usability is considered to be feasible for all EU28 countries for the research in this report.

After an extensive literature review and research process on available tools for food retail heat recovery assessment, the Danish Super Supermarket project is intended. The project funded by CLEAN, a cluster organization within energy and environmental technology – see [191, 192] – developed a calculation model for retail store heat recovery estimation. The calculation model was used for different Danish retail store cases from which specific data was collected, considering general and local conditions and is openly available. The model is used in the methodology described further in section 6.1 and was tailored for a European scale overall assessment, using the data available at the moment of the study.

Due to a general lack of sufficient data on food retail characteristics at facility level, food retail benchmarking indicators by area, and opening hours, along with country-specific climate data were used as inputs for the model, assuming a CO_2 trans-critical refrigeration system. From the calculation modes available, the model chosen only takes accessible excess heat in account (no distinction between available and accessible excess heat), since the technology type provides excess heat at a temperature that can be used directly for District Heating (DH), without heat pump requirement. Therefore, the heat will be used for food retail consumption foremost, as seen in the overview system in Figure 18.

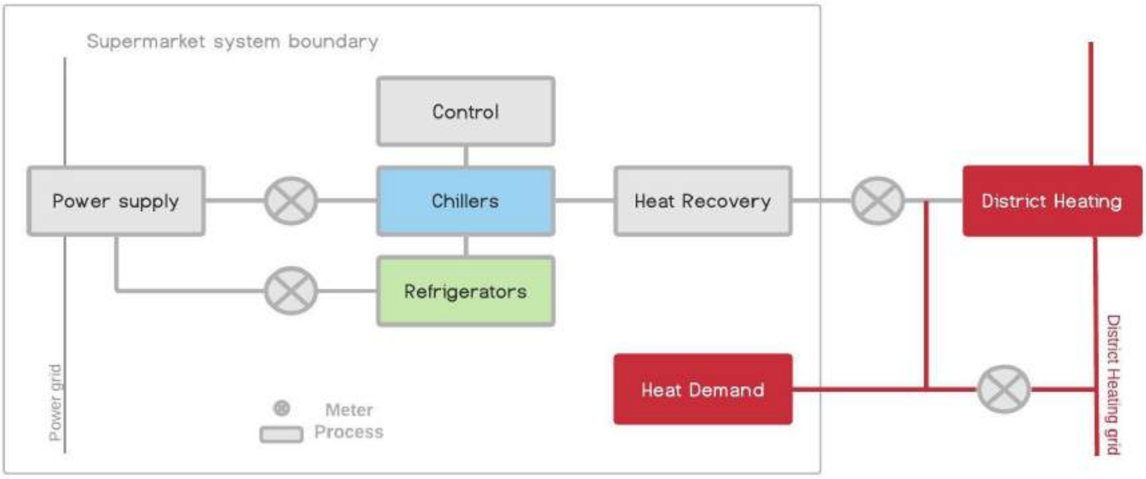

Figure 18. Technical setup from Super Supermarkets. Source: [192].

From research experience, specific data on a facility level for envisioned modelling of food retail heat recovery was not accessible, particularly spatial data. However, the consulted spatial source was tailored, linked and matched with additional databases in order to provide an overall analysis at an EU28 scale. From the sources investigated, it is known that food retailers - especially main food retail chains - often collect relevant data with regards to specific energy performance as metrics to support their energy management and resource efficiency. However, these data are frequently not publicly available and is therefore poorly exploited [178]. Notwithstanding, the methodology presented in section 6.1, and as depicted in Figure 19, serves as a model for excess heat estimation from the food retail sector and provides a spatial overview of the estimation when specific data on a facility level was not obtainable.

6.1 Methods

Figure 19 schematizes the overall methodology used for the mapping of excess heat potential coming from food retail refrigeration processes. It starts with food retail geo-identification and a mapping step, where food retail chains are filtered and selected from a larger GIS database containing multiple building typologies (OSM buildings database). Next, a floor area classification process based on investigated criteria is made and a subsequent model is used for each of the categories under that classification [Cat. 1,2,3,4&5]. In parallel, the process of excess heat estimation uses an already developed model. Here, a supermarket excess heat calculator developed by the Danish Super Supermarkets project [192] was chosen as the most adequate as for the available data from the food retail sector at an EU28 scale.

The considered inputs for the calculation model are average category floor area, food retail opening hours by category and country, and outdoor hourly temperature profiles. Space heat demand and typical cooling capacity are derived from the previous explained datasets. As pictured in Figure 18, the system's recovered heat goes either to DH or to cover the facility's internal heat demand, therefore the output of the model is an estimation of total and remaining heat accessible for DH from the food retail refrigeration system. The model also uses CO_2 systems as available technology for food retail stores, as explained above in section 6. Once the model's output is generated, the spatial mapping process is complemented when linking the two heat potentials to specific food retail building areas. Lastly, a 0 km (inside), 2 km, 5 km, and 10 km geospatial buffer analysis is performed to assess the distance from these food retail facilities to existing DH infrastructure. It incorporates into the analysis a potential spatial analysis for the heat that could be incorporated to the DH grid.

The four main stages of the methodology used for estimating the excess heat potential from the food retail sector can be visualized by means of different case colours, as in Figure 19, and which will be described further in sections 6.1.1 to 6.1.4.

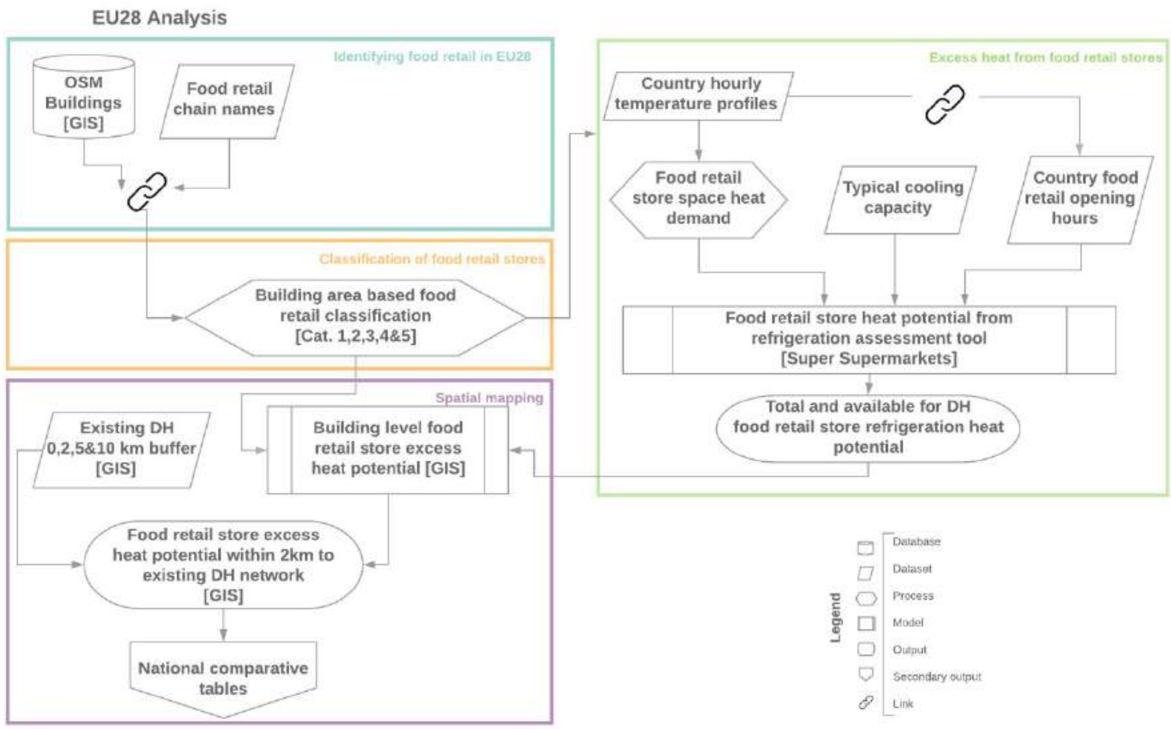

Figure 19. Food retail excess heat potential methodology.

6.1.1 Identifying food retail in EU28

In the analysis, the focus is on identifying food retail stores spatially explicit to find the excess heat potential within proximity to DH areas. Therefore, a top-down method based on e.g. statistical data on a regional scale is unattractive. A bottom-up approach is needed, where each store is identified separately. However, as this type of data is not part of any public database, an alternative option is needed.

Thus, OpenStreetMap (OSM) data is used to find the geographic location and buildings size (m^2) of food retail stores in EU28. OSM includes buildings as objects where each is represented by a polygon of the building plot. In the OSM, buildings are divided into 68 classifications of use, where food retail is one of them. Unfortunately, these classifications are not used in a consistent manner, as many food retails stores do not include a classification, while other non-food retail buildings are classified as food retail, such as for example shopping malls.

Yet, many buildings include a name of the building, which is a good identifier for food retail stores. To identify the food retail stores, a list of names of food retail stores in EU28 was created (see Table 63 in Appendix 15.9 for full list). The list is grouped by country and Figure 20 shows the total number of food retail chains per country, where the lowest number identified is five chains in Slovenia and the highest is Italy with 32 chains.

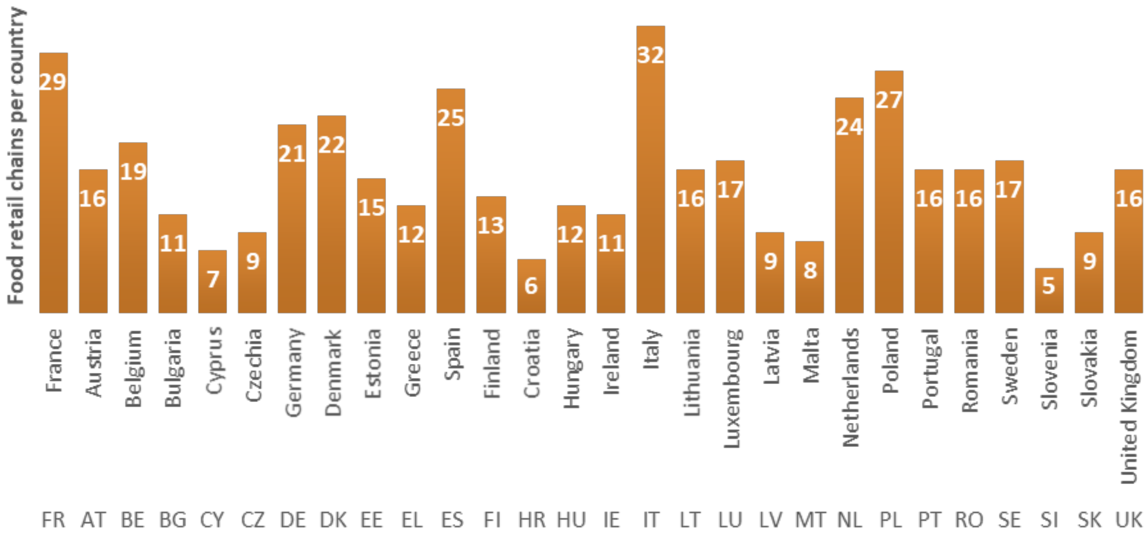

Figure 20. Number of food retail chains in EU28 (summary based on Appendix 15.9).

6.1.2 Classification of food retail stores

Food retail stores vary in size from small local stores to large hypermarkets. There are different classifications [177, 178, 193, 194] that could be used. The OSM data includes the specific ground floor area for each building, these floor areas are simplified to make the calculations feasible on an EU28 level. Hence, the food retail stores are grouped into five size categories based on [195], as described in Table 25:

Table 25. Food retail store sizing categorization. Source: [195]

Category N°	Description	Floor Area (m^2)
Cat1	Small food retail store	100-400
Cat2	Medium-sized food retail store	401-1000
Cat3	Large food retail store	1001-2500
Cat4	Small food retail store	2501-5000
Cat5	Large food retail store	> 5000

For each size category an estimate of the excess heat recovery potential is estimated for each country. This means that each food retail store within the same size category, in the same country, is assumed to have the same excess heat potential. In the following section, the methodology used to estimate these potentials is explained.

6.1.3 Excess heat from food retail stores

To assess the excess heat potential from food retail stores by each size category and country, a modified version of the assessment tool developed in the Danish research project Super Supermarkets [192] was used. The Danish project ended in December 2019, where a calculation model Beta version 0.92 was released, together with eight specific cases and a handbook on utilizing excess heat from food retail refrigeration.

The calculation model was made in Microsoft Excel and can be used to estimate heat recovery potentials from specific food retail stores. In reality, the heat recovery potential from a food retail store is based on e.g. local conditions, the specific setup of cooling system in each store, and how they are operated. A precise calculation of this would require a full hourly simulation of the cooling system in each store. A general Excel model therefore cannot make such a simulation and thus the calculation model uses a standardised cooling system which was simulated in the programming language EES (Engineering Equation Solver).

In essence, the model uses a predefined cooling system setup, representing an average food retail store. Furthermore, the model is split into summer and winter period and calculates average values for cooling performance and outdoor temperatures. The model also only includes three predefined forward and return temperatures for the heat production. From these assumptions it is possible to estimate efficiencies of the cooling units as a function of the heat production compared to the cooling performance. Finally, the calculation model is designed for economic feasibility studies, but in this report, we only use the technical outputs from the model. Figure 18 shows the technical setup, that is used in this report, the specific input values and data used is described in Section 6.2.

6.1.4 Spatial mapping

In this final step of the methodology, the modelled excess heat potentials by size category and country are joined with the spatial data from the OSM, to make a building level map of the excess heat potential in all of EU28. This spatial dataset on the EU28 potential at building level is then used together with the UMZDH-layer dataset on urban areas with district heating systems currently in operation to calculate the distances from each food retail store relative to these UMZDH areas. As for all other excess heat source categories investigated in this report, this calculation is performed by a Select by Location command for five given distances: 0 km (inside), 2 km, 5 km, 10 km, and farther than 10 km (outside), relative to the UMZDH areas.

6.2 Data

This section presents in more detail the data that has been used in the assessment of the excess heat potential from refrigeration processes in the food retail sector.

6.2.1 GIS data

In the analysis, OSM building data from 2019 was used [196]. By using the methodology described in Section 6.1.1, a total of 41,832 food retail stores (larger than 100 m^2) were identified with geographic location.

In terms of validation, it has not been possible to find a total number of food retail stores for all of EU28, however statistics were found for Spain, France, Italy, Belgium and Netherlands. According to Statista [197], the total number of stores in these five countries is around 46,475, while in the OSM dataset we only identified 9768 stores for the same countries, covering roughly 21%.

Furthermore, the share varies from country to country, with 81% in France as the highest to 5% in the Netherlands as the lowest, which illustrates that the method is more precise in countries with good OSM data coverage. As a result of this, the potentials found in this report can only be seen as the potentials that were possible to identify geographically, knowing that the full potential is higher.

Table 26 shows the food retail stores per country and size category. From the table it is clear that Germany (DE) (29.98%), the United Kingdom (UK) (11.79%) and France (FR) (10.85%), has more than half of the total number of food retail stores in the dataset.

Furthermore, the data shows that size category 3 (large food retail stores) is the largest group with 22,687 of the total 41,832 food retail stores (54%).

Table 26. Number of food retail stores per country by food retail size category

MS	Cat1	Cat2	Cat3	Cat4	Cat5	Sum	Percent of total
DE	224	1232	9672	745	668	12,541	29.98%
UK	854	913	1293	653	1218	4931	11.79%
FR	397	614	1795	1064	669	4539	10.85%
PL	392	852	1661	107	82	3094	7.40%
AT	144	693	1106	93	40	2076	4.96%
ES	105	201	1024	395	211	1936	4.63%
IT	80	275	750	228	221	1554	3.71%
DK	38	550	731	106	25	1450	3.47%
BE	75	233	756	257	75	1396	3.34%
HU	186	302	604	31	121	1244	2.97%
SE	62	261	381	100	82	886	2.12%
FI	42	195	342	112	85	776	1.86%
PT	50	50	374	147	123	744	1.78%
RO	35	81	302	63	179	660	1.58%
SK	170	131	219	61	53	634	1.52%
CZ	13	28	378	87	121	627	1.50%
LT	98	152	210	108	35	603	1.44%
SI	47	100	204	44	24	419	1.00%
IE	34	29	246	45	13	367	0.88%
NL	36	79	192	29	7	343	0.82%
HR	39	30	106	58	35	268	0.64%
LV	25	77	59	23	6	190	0.45%
EL	8	30	106	8	4	156	0.37%
BG	8	19	82	17	25	151	0.36%
EE	39	48	44	13	4	148	0.35%
LU	5	11	28	9	11	64	0.15%
CY	1	2	15	7	1	26	0.06%
MT	1	-	7	-	1	9	0.02%
TOTAL	**3208**	**7188**	**22,687**	**4610**	**4139**	**41,832**	**100%**

Finally, Figure 21 shows two maps of the food retail stores identified in Berlin (as an example). The left map shows the five size categories while the map to the right shows the detailed building level.

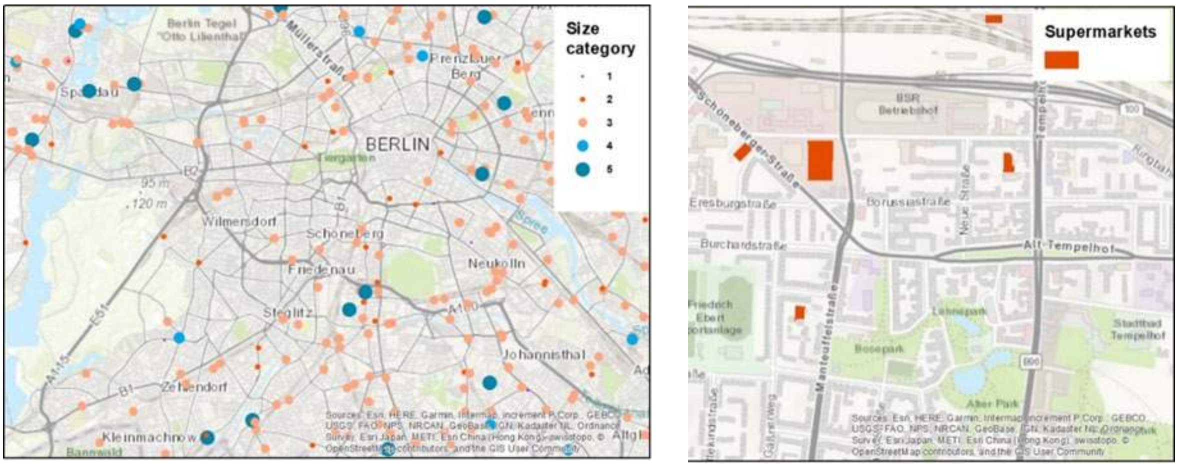

Figure 21.Map of food retail stores identified by OSM data (Berlin example).

6.2.2 Excess heat estimation data

Multiple data inputs are required to estimate the excess heat demand for each food retail size category per country. Some of these data inputs are constant, while others vary from country to country. The inputs that vary are temperatures, opening hours and heat demands, which will be explained separately after the constant inputs.

The maximum cooling capacities for food retail store size 1, 2, 3, 4, 5 are assumed to be 60 kW, 150 kW, 240 kW, 300 kW and 400 kW, respectively [193]. Some of these constant values are based on default values from the calculation model from the Super Supermarkets Project [192].

The DH forward and return temperatures from April to September are assumed to be 60°C/30°C and from October to March 70°C/40°C, temperature levels which are chosen to reflect more modern heat distribution systems and which typically are somewhat lower than current European systems.

The share of cooling load from cooling rooms of MT load is assumed to be 25%, the share of cooling load from greens and vegetables 25%, the cooling load from LT as a share of cooling load of MT is assumed to be 50%. These cooling shares will in practice vary between retail stores, but to attain this knowledge would require site-specific data collection.

As mentioned, some parameters vary from country to country, namely outdoor temperatures and opening hours. In the calculation model outdoor temperatures (T_{out}) and opening hours are used to calculate the following inputs:

- Number of hours from 1/10-31/3 where T_{out} >10°C
- Number of opening hours from 1/4-30/9 where T_{out} <10°C
- Number of closed hours from 1/4-30/9 where T_{out} <10°C
- Average temp of opening hours from 1/4-30/9 where T_{out} >10°C
- Average temp of closed hours from 1/4-30/9 where T_{out} >10°C
- Opening hours in the summer (1/4-30/9)
- Closing hours in the summer (1/4-30/9)
- Average opening hours

For both the outdoor temperatures and opening hours, hourly values for all of EU28 was used. For an overview of the data, Appendix 15.10 presents the monthly and yearly average outdoor temperatures for each country in the EU28 (Table 64). Furthermore, Appendix 15.10 also shows the opening hours by country for each food retail store size category and for Monday-Friday, Saturdays and Sundays (Table 65).

The excess heat production from food retail refrigeration is typically used internally in the store, and only the heat that is not used internally will be available for DH purposes. Therefore, it is necessary to estimate how large heat demands the food retail stores have. The heat demand in food retail is primarily due to a need for space heating and domestic hot water, of which the first is correlated to the outdoor temperatures in each location.

The outdoor temperatures changes over the year, but the space heat demand can be estimated based on heating degree days (HDDs). Table 27 includes the HDDs per month, for winter and summer with a derived index number based on the HDDs in Denmark. The reason for using Denmark is that it was possible to find an average specific heat demand [MJ/m^2] for Denmark for both summer and winter.

Table 27. Heating degree days per country (17°C base temperature) with data from [4]. Denmark is highlighted as it is the base of the index values in the last two columns

MS	Heating degree days (HDDs)														Index	
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**S[1]**	**W[2]**	**S[1]**	**W[2]**
FI	765	726	671	441	273	139	62	100	244	430	575	702	1,260	3,868.37	1.73	1.62
SE	646	602	577	385	235	119	56	76	195	367	491	604	1,066	3,286.89	1.46	1.37
EE	619	600	557	343	192	96	33	47	158	318	450	575	869	3,119.71	1.19	1.30
LV	592	561	518	322	179	92	32	41	144	296	423	540	810	2,929.13	1.11	1.22
LT	591	529	470	272	135	71	26	32	127	268	400	539	661	2,797.81	0.91	1.17
PL	577	501	457	270	136	75	32	37	131	260	392	530	681	2,716.36	0.94	1.14
CZ	577	476	429	251	125	71	41	41	132	253	390	540	661	2,665.53	0.91	1.11
SK	604	496	418	227	106	61	32	33	123	244	383	551	583	2,695.51	0.80	1.13
DK	485	443	428	284	171	95	36	37	106	236	342	458	728	2,391.42	1.00	1.00
SI	543	454	383	248	112	53	28	31	120	209	351	503	591	2,443.52	0.81	1.02
DE	494	425	391	246	128	71	39	39	111	222	350	473	633	2,354.96	0.87	0.98
AT	566	439	360	203	86	40	24	25	99	210	368	526	477	2,468.37	0.65	1.03
LU	487	405	357	226	117	60	40	36	104	208	341	463	583	2,260.65	0.80	0.95
BE	442	377	346	235	129	71	45	41	98	193	313	432	619	2,102.58	0.85	0.88
HU	546	440	343	161	61	29	12	13	77	185	338	510	352	2,361.83	0.48	0.99
UK	371	341	332	257	176	106	71	66	112	195	286	376	788	1,900.14	1.08	0.79
RO	554	447	335	177	61	22	6	7	65	175	325	508	338	2,344.25	0.46	0.98
NL	401	358	345	230	131	71	34	29	74	173	275	396	568	1,947.66	0.78	0.81
IE	333	307	302	250	176	106	71	67	109	187	263	328	779	1,720.17	1.07	0.72
BG	507	404	305	176	62	19	3	5	45	137	289	461	310	2,104.28	0.43	0.88
IT	440	374	303	211	81	27	6	7	58	130	281	408	388	1,935.98	0.53	0.81
FR	347	295	250	171	78	27	11	12	46	107	235	340	346	1,574.94	0.48	0.66
HR	370	299	219	100	20	6	0	0	20	72	197	332	147	1,488.30	0.20	0.62
PT	267	211	170	139	72	22	12	10	22	63	176	249	277	1,136.54	0.38	0.48
EL	310	262	191	101	24	2	-	-	5	41	146	263	132	1,213.97	0.18	0.51
ES	260	206	152	113	48	9	2	1	11	48	164	245	185	1,075.00	0.25	0.45
MT	144	145	109	61	12	1	-	-	-	1	29	91	74	518.76	0.10	0.22
CY	150	133	91	37	5	-	-	-	-	2	36	105	42	517.25	0.06	0.22

[1]Summer
[2]Winter

The specific heat demand columns in Table 28 are the result from combining the summer and winter index numbers from Table 27 with Danish winter and summer heat demands of respectively 274 MJ/m^2 and 83 MJ/m^2. These specific heat demands are multiplied with average ground floor area of each food retail size category (1-5).

The average ground floor areas used are 200 m^2, 700 m^2, 1750 m^2, 3750 m^2 and 10,000 m^2 for category 1, 2, 3, 4 and 5, respectively.

Table 28. Estimated heat demand per food retail store by country, season and food retail type

MS	Specific heat demand [MJ/m²]		Heat demand per building for each food retail size category [TJ/year]									
			Cat1	Cat2	Cat3	Cat4	Cat5	Cat1	Cat2	Cat3	Cat4	Cat5
	W²	S¹	W²					S¹				
BE	246	77	0.05	0.17	0.43	0.92	2.46	0.02	0.05	0.14	0.29	0.77
BG	246	60	0.05	0.17	0.43	0.92	2.46	0.01	0.04	0.10	0.22	0.60
CZ	300	80	0.06	0.21	0.53	1.13	3.00	0.02	0.06	0.14	0.30	0.80
DK	274	83	0.05	0.19	0.48	1.03	2.74	0.02	0.06	0.15	0.31	0.83
DE	270	78	0.05	0.19	0.47	1.01	2.70	0.02	0.05	0.14	0.29	0.78
EE	345	92	0.07	0.24	0.60	1.29	3.45	0.02	0.06	0.16	0.34	0.92
IE	209	86	0.04	0.15	0.37	0.78	2.09	0.02	0.06	0.15	0.32	0.86
EL	160	49	0.03	0.11	0.28	0.60	1.60	0.01	0.03	0.09	0.19	0.49
ES	146	52	0.03	0.10	0.26	0.55	1.46	0.01	0.04	0.09	0.20	0.52
FR	195	62	0.04	0.14	0.34	0.73	1.95	0.01	0.04	0.11	0.23	0.62
HR	186	50	0.04	0.13	0.33	0.70	1.86	0.01	0.04	0.09	0.19	0.50
IT	230	64	0.05	0.16	0.40	0.86	2.30	0.01	0.04	0.11	0.24	0.64
CY	92	44	0.02	0.06	0.16	0.34	0.92	0.01	0.03	0.08	0.17	0.44
LV	326	88	0.07	0.23	0.57	1.22	3.26	0.02	0.06	0.15	0.33	0.88
LT	313	80	0.06	0.22	0.55	1.18	3.13	0.02	0.06	0.14	0.30	0.80
LU	261	75	0.05	0.18	0.46	0.98	2.61	0.02	0.05	0.13	0.28	0.75
HU	271	62	0.05	0.19	0.47	1.02	2.71	0.01	0.04	0.11	0.23	0.62
MT	92	46	0.02	0.06	0.16	0.35	0.92	0.01	0.03	0.08	0.17	0.46
NL	231	74	0.05	0.16	0.40	0.87	2.31	0.01	0.05	0.13	0.28	0.74
AT	281	69	0.06	0.20	0.49	1.06	2.81	0.01	0.05	0.12	0.26	0.69
PL	305	81	0.06	0.21	0.53	1.15	3.05	0.02	0.06	0.14	0.30	0.81
PT	152	58	0.03	0.11	0.27	0.57	1.52	0.01	0.04	0.10	0.22	0.58
RO	269	61	0.05	0.19	0.47	1.01	2.69	0.01	0.04	0.11	0.23	0.61
SI	279	76	0.06	0.20	0.49	1.05	2.79	0.02	0.05	0.13	0.28	0.76
SK	303	75	0.06	0.21	0.53	1.14	3.03	0.02	0.05	0.13	0.28	0.75
FI	417	114	0.08	0.29	0.73	1.56	4.17	0.02	0.08	0.20	0.43	1.14
SE	361	103	0.07	0.25	0.63	1.35	3.61	0.02	0.07	0.18	0.39	1.03
UK	226	87	0.05	0.16	0.40	0.85	2.26	0.02	0.06	0.15	0.33	0.87
EU28	250	72	0.05	0.17	0.44	0.94	2.50	0.01	0.05	0.13	0.27	0.72

¹Summer
²Winter

6.3 Results

The resulting excess heat potentials for EU28 from food retail refrigeration are presented in maps and tables. Firstly, the excess heat potential per facility is presented, secondly the national potentials and maps for EU28 are presented, and thirdly the presentation of the national potentials under the default spatial restraint.

It should be noted, due to the modelling of trans-critical CO_2 systems for the entire EU28, and the relatively high temperatures of rejected heat from these systems, that, volumetrically, no difference is made for this sector regarding available vs. accessible excess heat. As no heat pumps are anticipated here, the excess heat potential has therefore been labelled "accessible" in the following, on the one hand for the complete study population, on the other hand, for those food retail stores that, after spatial analysis with regards to current district heating areas, are found inside or within 2 kilometres from these areas.

Figure 22 shows the full accessible excess heat potential, after internal use, per facility and for each country and size category. In this figure, the countries have been sorted from the highest to the lowest potential per facility.

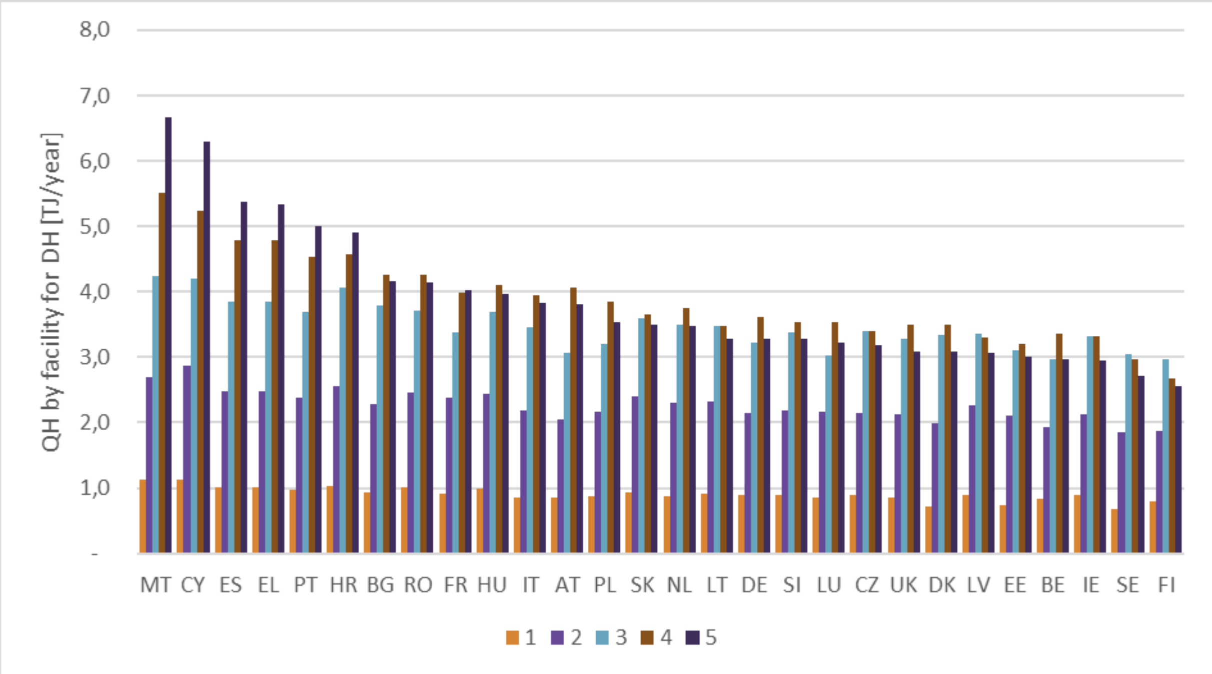

Figure 22. Accessible excess heat obtainable for DH by country and food retail size category.

The result illustrates that the countries in southern Europe have higher potentials than the northern European countries. However, it should be noted that the heat demand in buildings, and thus for DH, is typically lower in these countries as well, thus reducing the actual practical implementation potential.

Another aspect of the result is the difference between the food retail size categories, where the smaller stores could be expected to produce less excess heat than the larger ones. However, as part of the excess heat is used for internal purposes in the retail stores, the potential in colder climates are significantly reduced. Thus, the potential (remaining after internal use) for the same size of retail store in Finland is only 2.5 TJ/year while for the same store in Malta is 6.7 TJ/year.

The map in Figure 23 shows the full accessible excess heat potential from refrigeration processes in the food retail sector. Based on the map, the potential seems to be distributed widely across the EU28, which is expected as retail stores are present in most cities.

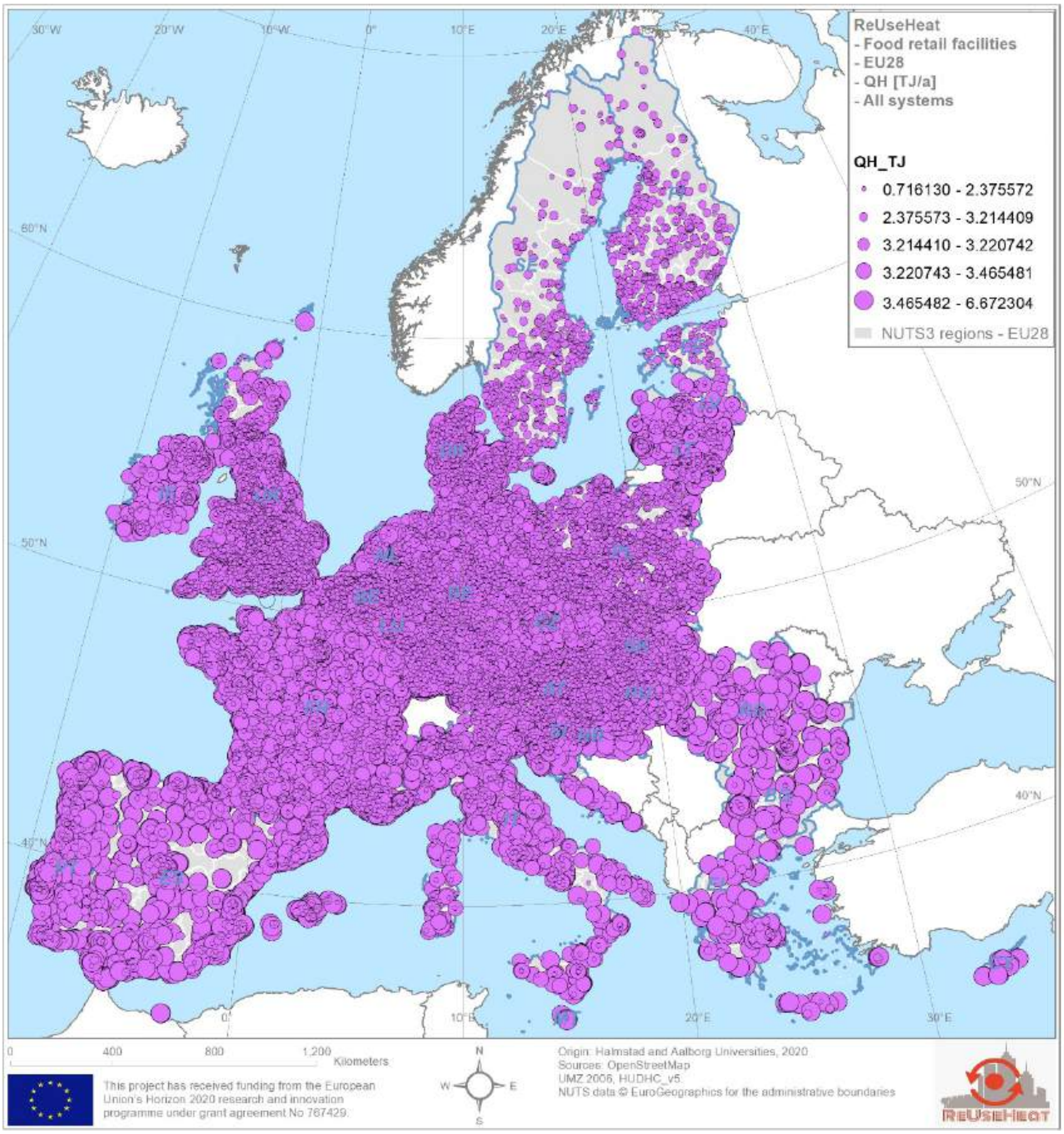

Figure 23. Accessible excess heat from 41,832 EU28 food retail stores.

Table 29 shows both the aggregated potentials and average potential per facility by country. The aggregated potentials show that larger countries, e.g. Germany, France, Poland, and the United Kingdom, has around 100 PJ of the full potential 158.7 PJ. The difference between accessible excess heat by facility and accessible excess heat by facility for DH, shows what was explained earlier, that due to larger heat demand in the stores in colder climates, the heat available for district heating is below the average EU28 average.

Table 29. Total accessible excess heat potential from the food retail sector, in total heat volume and the heat obtainable by district heating (DH). Furthermore, the anticipated average heat volumes by facility is also given. Please note that the table does not distinguish the available heat volumes, as boosting of temperatures is not needed for this sector

MS	QH [PJ]	QH for DH [PJ]	QH by facility [TJ/n]	QH by facility for DH [TJ/n]
AT	6.6	5.5	3.2	2.6
BE	4.9	3.8	3.5	2.8
BG	0.7	0.5	4.5	3.6
CY	0.1	0.1	4.7	4.3
CZ	2.8	2.0	4.5	3.3
DE	48.3	38.9	3.8	3.1
DK	4.8	4.0	3.3	2.8
EE	0.4	0.3	2.8	2.2
EL	0.6	0.6	3.9	3.5
ES	8.7	7.6	4.5	3.9
FI	2.9	1.9	3.7	2.5
FR	18.5	14.8	4.1	3.3
HR	1.2	1.0	4.4	3.7
HU	4.6	3.8	3.7	3.0
IE	1.3	1.1	3.6	3.0
IT	6.4	5.0	4.1	3.2
LT	2.1	1.7	3.5	2.8
LU	0.2	0.2	3.8	2.8
LV	0.6	0.5	3.2	2.6
MT	0.0	0.0	4.5	4.2
NL	1.2	1.0	3.5	3.0
PL	10.0	8.2	3.2	2.7
PT	3.3	2.8	4.5	3.8
RO	3.2	2.4	4.9	3.6
SE	3.1	2.2	3.5	2.5
SI	1.5	1.2	3.5	2.8
SK	2.1	1.7	3.3	2.6
UK	18.5	13.0	3.8	2.6
EU28	**158.7**	**125.7**	**3.8**	**3.0**

Since for this sector, the assessed excess heat volumes correspond to recoverable energy at sufficiently high temperatures for direct utilisation in district heating systems, these are expressed here as "accessible" excess heat. But, to maintain the main study approach, this total accessible excess heat potential was as well subjected to the spatial analysis relative current urban district heating areas (UMZDH areas), according to the same predefined distance classes of "inside", "within 2, 5, 10 kilometre", and "outside", as performed for all other source categories investigated in this work.

Given that this sector represents by far that with the largest count of unique activities (41,832, as presented above in Table 26), it might be worthwhile to account for the complete distribution of these with reference to the five distance classes. A total of 18,233 stores were found to be located inside the UMZDH areas (44%). Another 1938 within 2 kilometres of these areas (5%), which generates a total count found to meet the study default setting (inside or within 2 kilometres) of 20,171 stores (48%), presented in Table 30. 2872 (7%) were found in the 2 km – 5 km interval, and another 3693 (9%) within the 5 km – 19 km interval, which implies that a total of 26,736 stores (64%) are located inside or within 10 kilometres of current urban district heating areas. A remainder of 15,096 stores (36%) were found to be located beyond 10 kilometres of these areas.

Table 30. Total count and accessible excess heat potential for food retail stores inside or within 2 kilometres of current urban district heating areas

MS	Food retail stores (2km) [n]	QH (2km) [PJ]
AT	1272	3.5
BE	942	2.6
BG	100	0.4
CZ	571	1.9
DE	4712	14.5
DK	1055	3.0
EE	117	0.3
ES	364	1.4
FI	539	1.3
FR	1759	5.7
HR	117	0.4
HU	791	2.6
IE	96	0.3
IT	453	1.5
LT	403	1.2
LU	22	0.1
LV	139	0.4
NL	75	0.2
PL	2468	6.7
PT	90	0.3
RO	446	1.6
SE	578	1.5
SI	261	0.8
SK	469	1.4
UK	2332	6.0
EU28	**20,171**	**59.7**

As can be seen in Table 30, in terms of the spatially weighted accessible excess heat potential from the food retail sector, this is found at some 60 PJ per year, which constitute approximately 47% of the full potential available for district heat distribution (126 PJ per year). Germany, Poland, and the United Kingdom stand out among the 25 member states with annual accessible excess heat volumes assessed at 14.5 PJ, 6.7 PJ, and 6.0 PJ per year respectively. It should be noted that Greece was exempted from this spatial analytical step due to reasons explained in section 2.3.1 above.

6.4 Comments

The modelling of excess heat from retail refrigeration is a first attempt at an EU28 wide assessment and therefore includes several simplifications that will be discussed in the following.

The main data input used in the report is based on building polygons from OpenStreetMap (OSM) and a manual selection based on a list of retail store chains in each EU country. As OSM is an open source dataset, the data quality in terms of coverage varies a lot between countries, giving large uncertainties in countries with low coverage. However, for the buildings that are included in OSM, the quality is quite good as it includes the actual building area as a polygon, as opposite to other databases where the information is only available as point data. As a result of the low coverage in some countries, the potentials identified in this report are conservative estimates, as the estimates only includes the buildings that could be georeferenced. Furthermore, the selection based on retail store name is a further reduction, as the list of names could be incomplete and the OSM in many cases could be missing the information. Some examples of the latter are Greece and Netherlands, where very few retail stores were identified in the dataset in relation to what could be expected.

Food retail stores are different across the EU28, both in terms of size, the actual layout of refrigerators and energy consumption. A simplified modelling setup was applied in order to include the main differences between stores. Here the categorisation of retail stores into five size categories is a simplification, that gives a lower quality of the result than if e.g. the individual size of each store was used. However, the step was needed to make the processing possible. Also, using the total area of the buildings for the categorisation is a simplification, as the literature review points at the store area as being a better indicator. It was however not possible to attain store areas for EU28, so again this was simplified in the model.

Another data input that was simplified is the temperature sets used, mainly due to availability, as the model only uses a single temperature for each country. This gives uncertainties in countries with a large variation in climate, e.g. Italy where the north is much colder than the south. Furthermore, the temperature data is only based on data for a single year, which gives larger uncertainties than using e.g. a period of 10 years. In relation to the temperatures, the model also uses a simplification related to summer and winter, where the year is split into two halves based on fixed months. This division between summer and winter is assumed to be the same for all countries, where a more detailed model could have included e.g. larger summer period in warmer areas.

In terms of the model used to assess the excess heat potential, the model is considered to be quite detailed for a broad spatial analysis, as it would normally be used for specific case studies. To be able to use it this way, some general assumptions were used, that would be different in a case study. Here the most important is the layout of refrigerators, with fixed shares of different types of refrigeration. This has a large impact on the potential in specific cases but was necessary due to the large amount of food retail stores in EU28.

In regard to estimates of heat available for district heating there are uncertainties as well, the modelling of heat consumption for each building is based on fixed classifications of buildings, and thus the internal building demands could be both smaller and larger than what is assumed in the model. Furthermore, the results only show the heat that is available for district heating, but it does not consider if and when there is district heat demand in each country. Including this, would have the opposite effect on the result compared to the internal demand calculations, as countries with colder climate could also be assumed to have a larger demand for district heat than warmer countries with low demand. An example of this could be that in the analysis the excess heat from a food retail store in Malta is quite high, however the demand for district heat would most likely be very low.

All in all, besides the simplification described above, the model presented in this report for excess heat estimation of food retail stores, is considered good for a general estimate that can be used further to identify specific cases and make more in-depth evaluation of the case specific potentials.

7 Cooling of service sector buildings

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 excess heat potentials for this source category has been conceived. This removal of heat, or supply of cold, can in practice be arranged in several various ways, depending e.g. on the scale of the application. For service sector buildings, which here includes the complete sector, such as offices, hospitals, education activities, public administration etc. (as specified in Table 4 above), central cooling devices constitutes the considered technology.

Key for the modelling in this study, therefore, has been the availability of quantitative data on current cooling demands for the EU28 service sector, as well as information on the saturation level by which current cooling demands is actually satisfied. For the spatial mapping, correspondingly, the availability of geographical datasets by which the distribution of service sector buildings is determined, has likewise been highly relevant. As is further detailed in section 7.2 below, all these required data parameters have been successfully retrieved from various sources, which has rendered the modelling possible.

It may also be noted that, to our current knowledge, no previous study has so far attempted to assess the excess heat potential from rejected heat associated to cooling processes in service sector buildings. Hence, no references have been found that explicitly addresses this topic, although a few studies have provided quantitative assessments of European space cooling demands [198, 199], while some others have studied district cooling in European [200], as well as in international contexts [201-203]. Some additional sources has also been utilised here with respect to energy and environmental characteristics of air conditioning systems [204, 205], as well as that of a reference study which mapped service sector cooling demands by means of a raster grid at hectare resolution (albeit limited to 14 EU28 member states) [51].

As will be described in the following, the modelling of this source category has been performed in quite a straight-forward fashion, involving basically three steps: determination of service sector cooling demands (and shares of cooled surface areas), calculations of excess heat potentials, and, consistently, spatial correlation to current urban district heating areas. The data and modelling accuracy level throughout this sequence is considered quite high, however, with one major shortcoming. In brief, this weakness consists in a uniform spatial distribution of assessed shares of cooled surface areas, over the complete floor-area raster dataset used, which is likely not representative of actual spatial concentrations of (satisfied) service sector cooling demands to city centre areas.

7.1 Methods

The recovery of excess heat from cooling processes in service sector buildings is here conceived as taking place in two-stage configuration set-ups. In the first stage, heat is apprehended principally as being removed from incoming air, by means of central cooling devices, such as CAC (central air-conditioning) units, to maintain desired indoor room temperatures over the annual cycle. In the second stage, the rejected heat from these central cooling devices, with the electrical energy introduced in the process added, is considered equivalent to that of available excess heat possible to recover by means of large-scale heat pumps, and thus constitute Q_L in the (heat pump) modelling of this source category. To assess the average efficiency in such central air-conditioning conversions, an average EU28 SEER value (Seasonal Energy Efficiency Ratio) is used in order to assess the magnitudes of rejected heat from these processes.

Other alternatives, mainly individual cooling devices, such as RAC (room air-conditioning units), where heat often is removed directly from the indoor air itself, has not been considered here since these devices are more frequently associated with the residential sector. As central cooling devices, on the other hand, constitute the dominating application in service sector buildings [198], it is the preferred modelling preference in this study.

It should also be noted, that heat recoveries from service sector buildings may alternatively be arranged by one-stage configuration set-ups, albeit not further elaborated here. The main reason for not modelling this alternative is the temporal characteristics of this source category, i.e. both diurnal and seasonal variability, as indicated in Table 3 above, which diminishes the attractiveness and applicability of such arrangements. By a two-stage configuration set-up, rejected heat from building cooling processes may be thermally stored for later use when requisite heat demands for such usage is present.

In Table 3, further, the heat pump conversion type for this source category is stated as "Liquid-to-water", which is to indicate that the transfer of heat from central cooling machine condensers, to heat pump evaporators, may take place in the form of a refrigerant as well as in the form of water, depending on unique system technologies used in any given case. This is noted here for reference, but, given the general perspective maintained in the modelling of this work, not further elaborated in this context.

According to the above, the applied methodological sequence begins with the assembly of specific service sector cooling demands, which were gathered, on EU28 member state level for the year 2015, from the work performed in WP3 of the Heat Roadmap Europe project [199], as specified in Table 31 below. Likewise, information on the relative shares of total cooling demands actually satisfied by cold deliveries, expressed as shares of cooled surface areas, were retrieved from the same source (also presented in Table 31).

In terms of the spatial distribution of service sector buildings, two available sources of information were evaluated and compared. The first, an extract from the spatial mapping performed in WP2 of the Heat Roadmap Europe project [51], also displayed as an operational layer at the PETA 4.3 web map application [53], was incorporated in the study GIS geospatial database for reference (a dataset which is, as mentioned above, limited to 14 EU28 member states). This raster layer depicts, at hectare grid resolution, assessed cooling demands for the service sector, while the second dataset retrieved, the publicly available "non-residential sector" floor area hectare raster developed in the HotMaps project [206, 207] needed further elaboration to express 2015 cooling demands. In short, this was performed by raster calculations, where national specific cooling demands, as outlined in Table 31, were spatially associated to the distributed grid cells by each respective member state.

Next, equally by raster calculations, national shares of cooled surface areas were attributed in a similar fashion to all grid cells by each respective member state, whereby a distinction between full (total) cooling demands in the sector, and those met (satisfied) in 2015, could be established. The abovementioned shortcoming, i.e. that the shares of cooled surface areas were evenly distributed among the whole population of service sector grid cells, relates to this step in the sequence, and, as already stated, constitutes a weakness in the modelling that should be kept in mind when evaluating the outputs. In comment, it is more likely that the shares of cooled surface areas are higher in high density inner city urban areas, than, for example, at less concentrated locations. However, since no suitable data parameter by which to make this distinction was at hand, the modelling was done with this aspect unresolved.

As for the calculations of rejected heat from the anticipated central cooling devices, an average EU28 SEER value of 3.128, as established in a European space cooling demand study by Werner in 2016 [198], has been used uniformly in this modelling. The SEER value has been applied here as representing, on average, the practical COP for a refrigeration process ($COP_{R,p}$), which, again according to Dincer and Kanoglu [69], is defined as the heat absorbed from the cooling space (Q_L) divided by the work input to the compressor, according to:

$$COP_{R,p} = \frac{Q_L}{W} \quad [-] \qquad (17)$$

From this, and combined 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:

$$Q_H = Q_L\left(1 + \frac{1}{COP_{R,p}}\right) \qquad [-] \qquad (18)$$

In accordance with Equation (18), consequently, total volumes of rejected heat from the first stage in the elaborated two-stage configuration set-up, thus equivalent to available excess heat to be introduced to the second stage, constitute a factor 1.319 that of the heat absorbed from the cooling space itself.

For the spatial mapping, finally, geographical delineation with reference to current urban district heating areas were performed also for this source category, however, only by the criteria "completely within" such areas. The spatial dimension in terms of adjustment to local conditions is thus not established by the default "inside or within 2 kilometres of"-criteria consistently used for the other source categories. The reason for this is simply that the urban morphological zones dataset itself, upon which the UMZDH-layer is based, captures principally all service sector areas by definition.

7.2 Data

In this section, an account for the data used in this assessment is given by means of one table and one graph. First, in Table 31, national specific cooling demands, referring to the service sector, is presented in combination with shares of cooled surface areas, both retrieved from WP3 in the Heat Roadmap Europe project [199].

Table 31. Specific building cooling demands and shares of cooled surface areas for EU28 service sector buildings in 2015. Reproduction from Heat Roadmap Europe, WP3. Source: [199]

MS	Cooling demand [MJ/m²]	Share of cooled surface areas [%]
AT	259.9	8.3%
BE	189.7	23.8%
BG	306.4	28.3%
CY	868.7	84.7%
CZ	204.1	9.9%
DE	204.8	8.9%
DK	166.3	7.4%
EE	159.8	6.8%
EL	598.7	87.1%
ES	435.2	72.7%
FI	156.6	11.3%
FR	265.0	22.5%
HR	310.7	29.4%
HU	276.8	12.4%
IE	147.6	5.2%
IT	454.7	73.5%
LT	183.2	8.9%
LU	203.0	11.2%
LV	166.0	7.3%
MT	787.3	84.7%
NL	166.0	10.1%
PL	200.2	10.4%
PT	358.2	22.2%
RO	367.9	29.3%
SE	153.7	19.6%
SI	268.6	20.8%
SK	230.4	14.5%
UK	156.2	22.5%

As can be seen in this table, the southernmost EU28 member states, like e.g. Italy, Spain, and Greece, not to mention Cyprus and Malta, have, as can be expected, the highest specific cooling demands and likewise the highest shares of cooled surface areas. In terms of total volumes, as aggregated from the hectare grid cell basis at which they were calculated, five countries, once again Italy, Spain, and Greece, plus also France and Germany, clearly dominates the European service sector cooling market, as outlined in Figure 24.

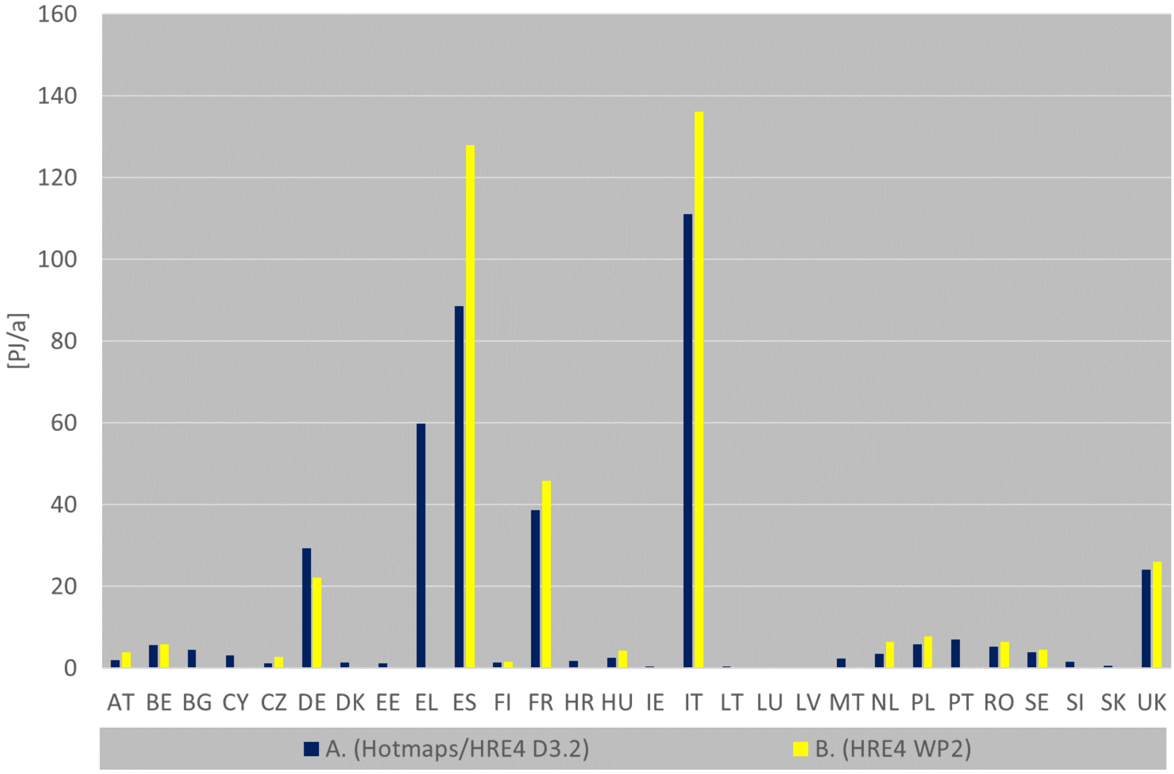

Figure 24. Comparison of service sector cooling demands assessed in: A. the used modelling dataset; B. the Heat Roadmap Europe WP2 assessment for 14 EU28 member states. Sources: [51, 199, 206].

The second service sector cooling demand assessments presented in Figure 24, i.e. the WP2 estimate for the 14 EU28 member states mapped in the Heat Roadmap Europe project (labelled "B"), serves the purpose here of constituting a benchmark by which to compare the dataset used for the modelling (labelled "A"). In general, despite some more marked deviances for Italy and Spain, the used dataset, i.e. the combined use of demands and shares (as presented in Table 31) and the HotMaps non-residential sector floor area raster layer, appears to be in reasonably fair correspondence with the HRE4 WP2 assessment.

7.3 Results

The available excess heat potential derived from rejected heat in building cooling processes, here thus anticipated for the entire EU28 service sector at current conditions and under the modelling assumptions accounted for above, is estimated at some 536 PJ per year, as presented in Table 32. In accordance with this, the total accessible excess heat potential, at a practical COP of 3.0, was found at 804 PJ, a figure which must be recognised as highly speculative, since it would imply complete recovery and utilisation of all currently rejected heat from this sector.

The service sector cooling demands of these cooled surface areas correspondingly sum up to a total of 406 PJ annually. This volume may be compared to those stipulated in other studies, as for example the 411 PJ per year of "estimated current cooling demand of service sector" estimated for the year 2016 by Jakubcionis and Carlsson in [208], or the 522 PJ suggested by Werner for the year 2010 in [198]. There are as well other estimates that has anticipated the current EU28 service sector cooling demand, one of which arrived at significantly higher total annual volumes (821 PJ, see the WP2.3 report from the Rescue project [200]). If not restricted to current shares of cooled surface areas, i.e. if considering a 100% saturation rate, the full cooling demand is estimated at 1287 PJ, at a total service sector floor area of 5259 square kilometres.

Table 32. Sum of service sector building cold demands (CD) in 2015 and assessed available excess heat at an average SEER of 3.128, and accessible excess heat at practical COP of 3.0

MS	CD [PJ]	QL 2015 [PJ]	QH COP 3.0 [PJ]
AT	2.0	2.6	3.9
BE	5.6	7.4	11.1
BG	4.4	5.7	8.6
CY	3.1	4.1	6.2
CZ	1.1	1.5	2.2
DE	29.4	38.7	58.1
DK	1.3	1.7	2.6
EE	1.1	1.4	2.1
EL	59.8	79.0	118.5
ES	88.5	116.8	175.1
FI	1.4	1.9	2.8
FR	38.7	51.0	76.6
HR	1.8	2.4	3.5
HU	2.5	3.3	4.9
IE	0.4	0.5	0.7
IT	110.9	146.4	219.6
LT	0.3	0.4	0.7
LU	0.1	0.2	0.3
LV	0.2	0.2	0.3
MT	2.2	2.9	4.4
NL	3.5	4.7	7.0
PL	5.8	7.7	11.5
PT	7.1	9.3	14.0
RO	5.2	6.9	10.3
SE	3.8	5.0	7.5
SI	1.6	2.1	3.1
SK	0.5	0.6	1.0
UK	24.1	31.8	47.8
EU28	**406.3**	**536.2**	**804.3**

From this comparison, it may be safe to conclude that the estimates presented here, at least does not overestimate current service sector cooling demands, which would be well in line with the general study precept of adhering to as conservative assessments as possible. Once more, it may be underlined that southern EU28 member states emerge as those that perhaps would benefit most from increased excess heat recoveries from this source category, albeit rich opportunities are present also in many Central and Northern member states.

Now, if applying the schematic study delimitation with regards to spatial coherence and vicinity to current urban district heating areas, actualised for this source category only in terms of "completely inside" such areas, the effect is quite dramatic. By this step, only those segments of the service sector raster that are inside the 3280 UMZDH-layer areas are considered, with the result that the available excess heat potential is reduced to some 194 PJ (a reduction of approximately 64%), which is detailed in Table 33.

Correspondingly, the accessible excess heat potential under these limitations, at a practical COP of 3.0, is found at roughly 292 PJ, which, albeit more reasonable, still represents a volume accessible only under the assumption that all rejected heat from cooling processes in service sector buildings is recovered, an assumption which never may prove compatible with real-world events. As a reference, the 40 PJ potential of recoverable excess heat from hospitals only, as stipulated in the project proposal, constitutes only 5% of the full accessible EU28 excess heat potential modelled for this sector, and, under the given limitations, only a 14% fraction. This circumstance may therefore serve as a reminder that the potentials assessed for this source category is conditioned by a 100% recovery rate in all considered buildings.

Table 33. Available excess heat at SEER 3.128 and accessible excess heat at practical COP of 3.0 for service sector buildings inside urban district heating areas

MS	**QL 2015 (inside) [PJ]**	**QH COP 3.0 (inside) [PJ]**
AT	1.9	2.8
BE	5.5	8.3
BG	3.9	5.9
CY	0	0
CZ	1.2	1.7
DE	17.7	26.5
DK	1.3	1.9
EE	1.0	1.5
EL	-	-
ES	39.6	59.4
FI	1.4	2.2
FR	33.4	50.2
HR	1.7	2.6
HU	2.7	4.1
IE	0.3	0.4
IT	45.9	68.9
LT	0.3	0.4
LU	0.1	0.1
LV	0.2	0.3
MT	0	0
NL	1.6	2.4
PL	5.3	7.9
PT	3.2	4.8
RO	5.2	7.8
SE	3.6	5.4
SI	1.1	1.6
SK	0.5	0.7
UK	16.1	24.1
EU28	**194.3**	**291.5**

When performing spatial mapping by rasterization at such high levels of resolution as that of hectares, that is by 100 meter grid cells, and when doing so for the entirety of a vast land mass such as that of the EU28, it makes little sense to draw continental scale maps in order to illustrate the data. To still provide an example of the spatial detail by which the geographical distribution of service sector buildings has been mapped and perceived in this work, a close-up for the city area of Madrid (ES) is given in Figure 25. The legend scale in this map signifies the anticipated volumes of available excess heat possible to recover at each grid cell, in the unit GJ, and the clustering tendency of service sector activities to city centres is also markedly visible in this figure. The spatial spread of service sector buildings is also presented in the four demo-site maps in section 10.

If focussing on the second stage in the described two-stage configuration set-up used in this context, the rejected heat from central cooling devices in service sector buildings is assumed to be recovered in the temperature range between 30°C and 40°C, as outlined in Table 3. Noteworthy, the upper bound of this range may eventually be higher, since it at all times needs to be higher than the evaporation temperature in the cooling circuit for proper function. If comparing by the lowest of these two temperature values, i.e. 30°C, and relating this to an *ad hoc* annual average supply pipe temperature of 85°C for 3rd generation district heating systems, the theoretical COP value is found at 6.5. From this, an average Carnot efficiency of 46% may be conceived for this sector category.

In appendix 15.11, a complementary table with accessible excess heat volumes in service sector buildings located inside urban district heating areas, at practical COP values of 2.5 and 3.5, respectively, is included for reference, see Table 66.

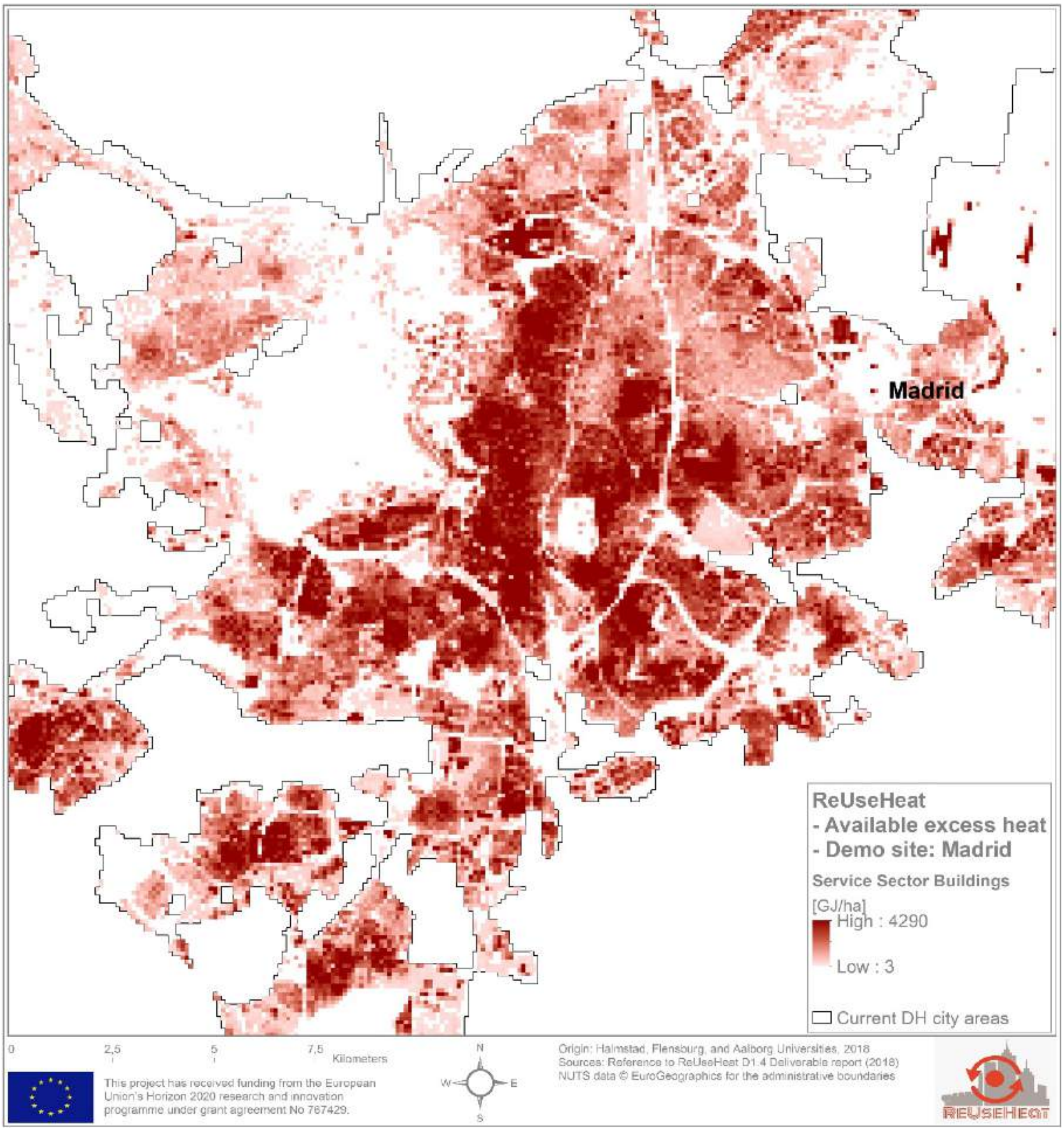

Figure 25. Available excess heat by hectare for service sector buildings. Close-up of the Madrid city area (ES).

7.4 Comments

Notably, when delimiting by UMZDH-layer areas, the excess heat potentials for the three member states Cyprus, Greece, and Malta, are reduced to nothing, as may be observed in Table 33. For Cyprus and Malta, this is the case since there simply are no accounts in the used datasets of any operating district heating systems in these countries, why no corresponding urban district heating areas are present in these instances. For Greece, however, a few district heating systems are in operation, according to the HUDHC_v5 dataset, however, since Greece is excluded from the used 2006 urban morphological zones dataset, for reasons unknown, no polygon representations for these Greece district heating systems has been available in the modelling. The original "null" values generated for

Greece by the model has therefore been replaced by a "-" to signify unavailability of input data.

While well determined by the spatial dimension, admittedly, the temporal dimension, i.e. diurnal, weekly, and seasonal variations, has not been explicitly considered in the modelling of this source category. In the main, for natural reasons, service sector building cooling demands are subject for seasonal variations given higher ambient temperatures in summer times, and further by geographical location. With respect to the latter, the cooling degree day number provides an indication as of the location-based magnitude of cool supplies required to maintain desired indoor temperatures. Implicitly, however, the temporal dimension was indeed included in this modelling, since the used quantitative data on specific cooling demands, as presented in Table 31, were established on the basis of these numbers in the original work. For an illustrative map of cooling degree day numbers distributed continuously over the EU28 land area, see figure 6 in [208].

Finally, one more time, it should be noted that shares of cooled surface areas was uniformly distributed to all member state grid cells respectively, which may not be representative of the actual distribution of such shares. Also, when reflecting on the mentioned circumstance that the assessed potentials assumes 100% recovery rates, which likely is far from achievable in a near future, this might be balanced by new emerging systems solutions, like for example that of Ectogrid [209]. In view of the main principle inherent to such low-temperature thermal district energy networks, in which heat and cold assets are equally manageable, it is likely that future recovery rates from service sector buildings will increase in the coming years.

8 Cooling of residential sector buildings**

In the original version of this report, this sector was excluded from the analysis of rejected heat from cooling of buildings, which instead focussed exclusively on the service sector. The main reason for this exclusion was a recognition of three general circumstances in current Europe: (1) that residential sector cold demands are relatively much smaller than those found in the service sector, (2) that the saturation rates (the actual use of cooling technologies to meet building cold demands) are generally significantly lower in the residential sector compared to the service sector, and (3) that the use of central cooling systems – which is a prerequisite for large-scale recovery and distribution in district heating systems- is of much lesser practice in the residential sector compared to the service sector.

The current supply for residential space cooling in EU28 has been estimated by several authors in recent years. By compilation in for example [210], this supply is reported in the range of 24 TWh to 56 TWh per year, where the lowest assessment, made by the Joint Research Center (JRC) for reference year 2009, is followed by Werner´s 2010 estimate at 47 TWh, Odyssee-Mure´s 2012 anticipation at 51 TWh, up to the highest assessment made by Kemna and Acedo for reference year 2010. For comparison, the "Space Cooling Technology Report in EU"-report from the Heat Roadmap Europe project [199], refers to some of the above mentioned studies while also referencing the 2014 EURAC assessment at 56 TWh per year, the Rescue project 2014 estimate at 57 TWh, as well as the 51 TWh per year own assessment (2015). From these sources, it is clear that current space cooling demands in residential buildings, relative to those associated with service sector buildings (where supplies, according to the same sources, range from approximately 130 to 380 TWh per year, at current saturation rates), constitute smaller annual volumes in general.

In terms of current saturation rates (a.k.a. "Share of cooled surface areas"), the differences between residential and service sector buildings in EU28 follow the same pattern as that for total supplies. According to [199], where the service sector EU28 average is given at 21.3%, the residential sector equivalent is stated at only 6.3% (both values referring to reference year 2015). The corresponding member state average saturation rate values for the residential sector are given in Table 36 below. Irrespective of a general agreement in the literature that these residential saturation rates will increase rapidly in the coming years (23% is anticipated for 2050 in the Heat Roadmap Europe context), it remains a fact for current year investigations that only a small fraction of residential buildings are equipped with some kind of cooling technology.

Furthermore, a majority of residential buildings in Europe which indeed do have cooling technologies installed, are equipped with individual units, i.e. movable and small split air-conditioning units, which are not compatible with large-scale recoveries of rejected heat. It is difficult to give an exact relative share as an average for EU28, but according to [199], which refers to current sales of various cooling technologies in the residential sector by member states, such individual systems account for approximately 65%-95% of national market sales. This provides an indication as of the remaining market segment supposedly occupied by residential sector central cooling systems, i.e. chillers in the 400-kW range and above, which here is conceived as the only cooling technology in this sector apt for excess heat recovery and utilisation by heat distribution.

As for the service sector assessment, the modelling approach for this source category has accordingly involved the basic steps of determining residential sector cooling demands (and shares of cooled surface areas), calculations of excess heat potentials, and, consistently, spatial correlation to current urban district heating areas – with the additional step of first making an appropriate selection of only those residential buildings where central cooling systems could be expected to exist. For this first step, the concept of plot ratio has been used based on a reference study (as explained in more detail below). The data and modelling accuracy level is considered quite high, however, with the same shortcoming as for the service sector assessment, namely uniform spatial distribution of assessed shares of cooled surface areas, which is likely not representative of actual spatial concentrations of (satisfied) residential sector cooling demands.

8.1 Methods

The basic approach for this assessment is identical to that performed above for the service sector. Hereby, the recovery of excess heat from cooling processes in a selected sub-set of residential buildings – a sub-set which is anticipated to only represent multi-family houses (MFH) with more than seven stories, as apt for central cooling systems - is here conceived as taking place in two-stage configuration set-ups. In the first stage, heat is apprehended principally as being removed from incoming air, by means of central cooling devices, such as CAC (central air-conditioning) units, to maintain desired indoor room temperatures over the annual cycle. In the second stage, the rejected heat from these central cooling devices, with the electrical energy introduced in the process added, is considered equivalent to that of available excess heat possible to recover by means of large-scale heat pumps, and thus constitute Q_L in the (heat pump) modelling. To assess the average efficiency in such central air-conditioning conversions, the same average EU28 SEER value as was used in the service sector assessment (3.128) has been used also here in order to assess the magnitudes of rejected heat from these processes. For further references and details, see section 7.1 above.

For the spatial mapping, as for the service sector again, geographical delineation with reference to current urban district heating areas were performed only by the criteria "completely within" such areas. The spatial dimension in terms of adjustment to local conditions is thus not established by the default "inside or within 2 kilometres of"-criteria consistently used for the other source categories. The reason for this is that the selected sub-set of high-density residential buildings are all principally located within urban morphological zones.

The first step for this assessment needed to consist of a selection of only those residential sector buildings which may be representative of the sector segment in which central cooling systems are applicable. The reason for this, as mentioned above, is that large-scale excess heat recovery is considered feasible only from such systems and not so from individual cooling technologies. In order to perform a systematic and fact-based selection, the concept of plot ratio (labelled "e", being the simple fraction of total floor area of a settlement and the total land area of the settlement, for references see for example [211]), was considered a useful metric. Among other applications, the concept is a key parameter in the district heat distribution capital cost model developed in [68] and has been frequently used in the European studies on investment costs for district heating, see for example [212].

To provide a set of benchmark values by which to distinguish between different typical residential building types, a classic Swedish report detailing these characteristics for 27 housing areas in Sweden [213] was digitalised and ordered by average plot ratio levels, as presented in Table 34. The abbreviated residential building types are single-family houses (SFH) and multi-family houses (MFH). As can be seen, multi-family housing, when approaching seven or more stories, are here associated with plot ratio values from approximately 0.40 to 0.70 and go well beyond plot ratio values of one for buildings with more than seven stories.

Table 34. Average plot ratio values for five different residential building types based on Swedish experience. Source: [213]

Residential building types	Average of Plot Ratio (e) [-]
1. SFH (Detached, concentrated)	0.22
2. SFH (concentrated, 1-2 stories)	0.27
3. MFH (1-3 stories)	0.34
4. MFH (2-7 stories)	0.70
5. MFH (>7 stories)	1.47

The main dataset used for this analysis was, in allegory and for comparability, gathered from the same source as that for the service sector assessment, i.e. the open data source repository of the HotMaps project [214]. This dataset will be further presented under section 8.2 below, but is presented here in Table 35 to facilitate a comparison with the benchmark regarding its characteristics.

Table 35. Characteristics of the residential sector gross floor area raster dataset used, by division into five residential building types segments based on plot ratio intervals. Source: [214]

Residential building types (with indicated plot ratio interval)	Land Area [ha]	Floor Area [ha]	Floor Area [%]	Avg. of plot ratio [-]	Max of plot ratio [-]
1. (e<0.1) Very Low - SFH (Detached, distributed)	34161515	585709	25%	0.05	0.10
2. (0.1<e<0.3) Low - SFH (Detached, concentrated)	5137608	895915	39%	0.20	0.30
3. (0.3<e<0.5) Medium - MFH (1-3 stories)	1148588	432348	19%	0.40	0.50
4. (0.5<e<1.0) High - MFH (2-7 stories)	465037	307200	13%	0.75	1.00
5. (e>1.0) Very High - MFH (> 7 stories)	79019	102896	4%	1.64	6.18
Grand Total	**40991767**	**2324068**	**100%**	**1.12**	

Here it is observable that the residential sector, hectare grid, cell raster dataset used for this analysis, includes some 41 million hectares with other than null data values, which correspond to approximately 9.4% of the EU28 total land area. This is fairly consistent with other studies, e.g. [212], where the total land area designated to building heat demands (however including also service sector buildings) was found to constitute roughly 9.2% of the total EU28 land area. Further, total EU28 residential floor areas sum at some 2.3 million hectares (or some 23.2 thousand km^2).

As can be seen in Table 35, further, 83% of total floor areas are found in the first three residential building type categories (25% + 39% + 19%), while 13% is characterised as having plot ratios between 0.5 and 1.0, and only a 4% fraction constitute the sector segment with residential high-density areas characterised by multi-family buildings with seven or more stories. To provide an illustration of the last two segments, Figure 26 shows to examples together with the unfiltered dataset (e >=0), one for a medium sized city (Malmö, Sweden), and one for a large metropolitan area (Paris, France).

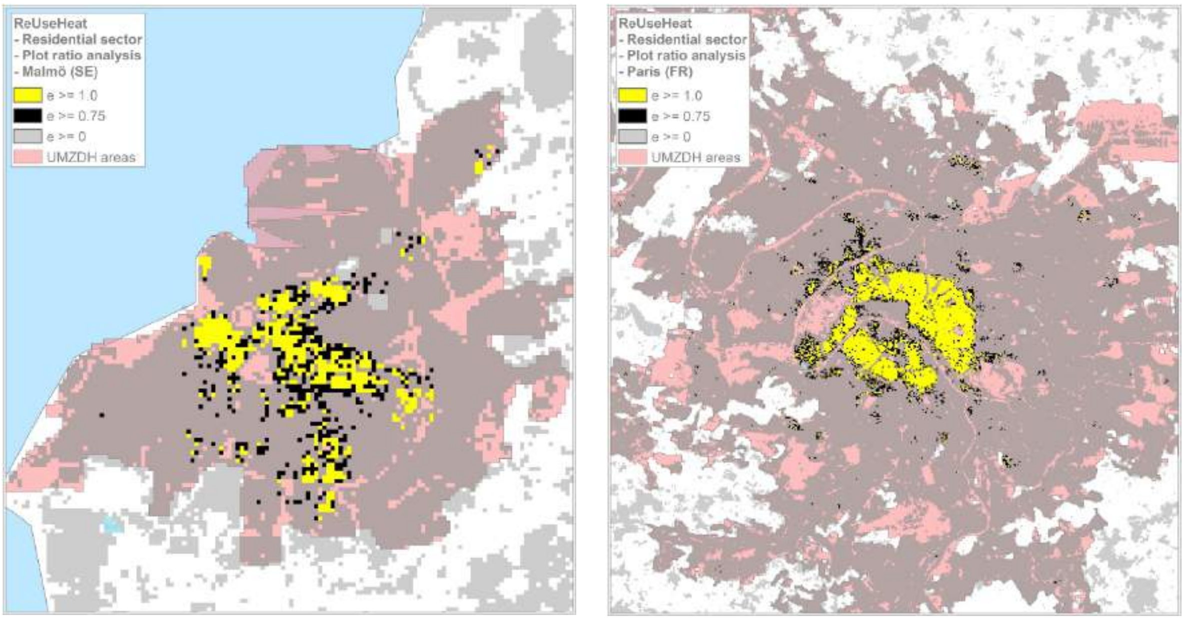

Figure 26. Illustration of plot ratio analysis for residential sector buildings at hectare level, at left for Malmö (SE), at right for Paris (FR).

Based on this plot ratio analysis, three different scenarios for the EU28 excess heat potential in the residential sector was performed: one for the unfiltered 2015 setting where saturation rates were applied (as reference), one for plot ratios at 0.75 and above, without saturation rates (not further accounted for in this context), and one – the selected scenario – for plot ratios at one and above, excluding saturation rates under the assumption that all of these buildings are equipped with central cooling systems.

8.2 Data

As a general basis for the excess heat assessment, data on specific cooling demands and shares of cooled surface areas in the EU28 residential sector, was gathered on member state level from the Heat Roadmap Europe project [199], as presented in Table 36.

Table 36. Specific building cooling demands and shares of cooled surface areas for EU28 residential sector buildings in 2015. Reproduction from Heat Roadmap Europe, WP3. Source: [199]

MS	Cooling demand [MJ/m^2]	Share of cooled surface areas [%]
AT	65.2	1.4%
BE	38.9	1.5%
BG	82.4	4.6%
CY	292.3	64.1%
CZ	44.3	1.3%
DE	44.6	0.4%
DK	30.2	0.7%
EE	27.7	0.4%
EL	191.5	22.9%
ES	130.7	14.2%
FI	26.6	0.3%
FR	67.0	5.9%
HR	83.9	6.5%
HU	71.3	2.8%
IE	23.0	0.3%
IT	137.9	17.8%
LT	36.4	1.0%
LU	43.9	2.0%
LV	29.9	0.5%
MT	262.1	52.9%
NL	29.9	0.7%
PL	42.8	0.8%
PT	101.9	3.8%
RO	105.5	7.5%
SE	25.6	0.7%
SI	68.4	4.4%
SK	54.0	2.7%
UK	26.3	0.4%

As for the service sector, the southernmost EU28 member states, like e.g. Italy, Spain, and Greece, not to mention Cyprus and Malta, have, as can be expected, the highest specific cooling demands and likewise the highest shares of cooled surface areas.

For the unfiltered 2015 setting, where both member state metrics in Table 36 were associated to the raster dataset by raster calculator operations (multiplication of floor areas (m^2) with specific heat demand (MJ/m^2) and with saturation rates (%)), a total EU28 residential cooling demand volume of 168 PJ (47 TWh) was found, as detailed in Table 37, which is well aligned with the introductory mentioned reports. In this sense the modelling of the 2015 reference scenario serves as a validation of the used data and approach, albeit it cannot serve as a basis for the excess heat potential assessment.

However, if imaginary only – as if all removed heat from all residential sector building would actually be recoverable, which it is not – the corresponding total available and accessible excess heat volumes at this 2015 reference setting, amounts to some 222 PJ and 333 PJ per year respectively (accessible heat at COP 3.0).

Table 37. Sum of all residential sector building cold demands (CD) in 2015, by saturation rates, and assessed available excess heat at an average SEER of 3.128, and accessible excess heat at practical COP of 3.0

MS	CD (2015 All) [PJ]	QL (2015 All) [PJ]	QH COP 3.0 (2015 All) [PJ]
AT	0.4	0.6	0.9
BE	0.3	0.4	0.6
BG	1.4	1.8	2.8
CY	7.6	10.1	15.1
CZ	0.2	0.3	0.5
DE	0.7	1.0	1.5
DK	0.1	0.1	0.1
EE	0.01	0.01	0.02
EL	22.7	29.9	44.9
ES	27.2	35.9	53.8
FI	0.02	0.03	0.04
FR	9.0	11.9	17.8
HR	0.7	0.9	1.3
HU	0.8	1.1	1.7
IE	0.01	0.02	0.03
IT	87.9	116.0	174.0
LT	0.04	0.06	0.08
LU	0.03	0.04	0.06
LV	0.01	0.01	0.02
MT	1.8	2.3	3.5
NL	0.1	0.2	0.3
PL	0.5	0.6	0.9
PT	1.4	1.8	2.8
RO	4.5	5.9	8.9
SE	0.1	0.2	0.2
SI	0.3	0.4	0.5
SK	0.2	0.2	0.3
UK	0.3	0.4	0.6
EU28	**168.4**	**222.2**	**333.3**

8.3 Results

The main results for the excess heat potential from cooling of buildings in the residential sector refer solely to the selected sub-set of multi-family buildings with seven or more stories, characterised by plot ratio values at one or above, since, in this context, this sector segment is the one most likely to be equipped with central cooling systems suitable for large-scale recovery. At this setting, no saturation rates have been applied since by the selection, only high-density area buildings are included, and the aim is to illustrate the full potential of this sector segment.

The available excess heat potential derived from rejected heat in residential building cooling processes, are here thus anticipated not for the entire EU28 residential sector, but for a representative extract. At current conditions, and under the modelling assumptions accounted for above, the available excess heat potential is therefore estimated at some 142 PJ per year, as presented in Table 38. The corresponding cooling demand for the selected sub-set is anticipated at 108 PJ. In accordance with this, the total accessible excess heat potential, at a practical COP of 3.0, was found at 213 PJ.

From this table it is clear that four member states; Italy, Spain, Greece, and France, host by far the largest shares of the current potential, which is natural since these four countries also represent the highest cooling demands.

Table 38. Sum of extracted residential sector building cold demands (CD) in 2015, with plot ratio, e, at one or above, no application of saturation rates, and assessed available excess heat at an average SEER of 3.128, and accessible excess heat at practical COP of 3.0

MS	CD (2015 e>=1) [PJ]	QL (2015 e>=1) [PJ]	QH COP 3.0 (2015 e>=1) [PJ]
AT	2.4	3.2	4.8
BE	0.6	0.9	1.3
BG	2.8	3.7	5.6
CY	0.1	0.2	0.3
CZ	0.3	0.3	0.5
DE	1.9	2.5	3.8
DK	0.3	0.4	0.7
EE	0.2	0.3	0.4
EL	12.0	15.9	23.8
ES	27.5	36.3	54.5
FI	0.1	0.1	0.2
FR	5.4	7.1	10.6
HR	0.01	0.02	0.02
HU	0.7	1.0	1.5
IE	0.01	0.02	0.03
IT	47.4	62.6	93.8
LT	0.1	0.2	0.3
LU	0.02	0.02	0.04
LV	0.01	0.01	0.02
MT	0.00	0.00	0.01
NL	0.1	0.1	0.1
PL	1.5	2.0	2.9
PT	0.1	0.1	0.2
RO	2.1	2.7	4.1
SE	1.3	1.7	2.5
SI	0.01	0.01	0.02
SK	0.01	0.01	0.02
UK	0.6	0.8	1.1
EU28	**107.7**	**142.1**	**213.2**

Now, if applying the schematic study delimitation with regards to spatial coherence and vicinity to current urban district heating areas, actualised for this source category only in terms of “completely inside” such areas, the effect is less dramatic compared to that of the service sector. This is however expected since the selected sub-set mainly consists of inner-city areas. By this step, accordingly, only those raster grid cells of the selected residential sector sub-set that are inside the 3280 UMZDH-layer areas are considered.

As outlined in Table 39, the final results for this source category indicate an available excess heat potential, inside current urban district heating areas, of approximately 73 PJ per year, which represents a reduction of 49% relative the 142 PJ per year potential at non-restricted spatial conditions. It should be noted that Greece was exempted from this final step of the analysis due to reason explained above in section 2.3.1. As for the other investigates source categories in this report, null values are also found for Cypris and Malta, since there are no records of district heating systems in the used input data. From this table it may analogously be concluded, once again, that member states with little, or no, deployment of district heating systems within their cities at current, despite perhaps considerable potentials, fall out of the assessment completely or have their accessible potential significantly reduced compared to their corresponding available potentials. Two such countries are Spain and Italy; whose accessible potentials are roughly only half of their corresponding available potentials.

Table 39. Available excess heat at SEER 3.128 and accessible excess heat at practical COP of 3.0 for extracted residential sector buildings, with plot ratio, e, at 1 or above, inside urban district heating areas

MS	QL (2015 e>=1) (inside) [PJ]	QH COP 3.0 (2015 e>=1) (inside) [PJ]
AT	3.2	4.8
BE	0.8	1.2
BG	3.3	5.0
CY	0	0
CZ	0.3	0.5
DE	2.5	3.8
DK	0.4	0.7
EE	0.3	0.4
EL	-	-
ES	17.6	26.3
FI	0.1	0.2
FR	7.1	10.6
HR	0.02	0.02
HU	1.0	1.5
IE	0.01	0.01
IT	29.5	44.2
LT	0.2	0.3
LU	0.01	0.02
LV	0.01	0.01
MT	0	0
NL	0.1	0.1
PL	1.9	2.8
PT	0.1	0.2
RO	2.6	3.9
SE	1.6	2.4
SI	0.01	0.02
SK	0.01	0.01
UK	0.5	0.8
EU28	**73.1**	**109.7**

When performing spatial mapping by rasterization at such high levels of resolution as that of hectares, that is by 100 meter grid cells, and when doing so for the entirety of a vast land mass such as that of the EU28, it makes little sense to draw continental scale maps in order to illustrate the data. To still provide an example of the spatial detail by which the geographical distribution of residential sector buildings has been mapped and perceived in this work, a close-up for the city area of Madrid (ES) is given in Figure 27.

The real value of a map like this is not really in its printing, but as a spatial operational layer in a web map application, where a user is able to extract the unique information of each particular grid cell. As for the map in Figure 27, the legend scale signifies the anticipated volumes of available excess heat possible to recover at each grid cell, in the unit GJ, and the map manages quit well to visualise the spatial extent of the selected sub-set for which the excess heat potential has been made.

From these results it is fair to conclude that, standing corrected, an assessment of the excess heat recovery potential from rejected heat from cooling processes in residential sector buildings in fact does have a righteous place in this report. Even at this restrained setting, i.e. even when only aiming to target the absolute high-density segment of the sector, the annual recovery potentials found are not entirely negligible. But it should indeed be kept in mind that the actual presence of central cooling systems in this sector segment, by no means has been possible to verify in this context. In this sense, this particular assessment must be regarded as a case of speculative modelling, although the used input data is of high quality and accuracy. A complementary table with accessible excess heat volumes at practical COP values of 2.5 and 3.5, respectively, is included for reference in Table 67 in Appendix 15.12.

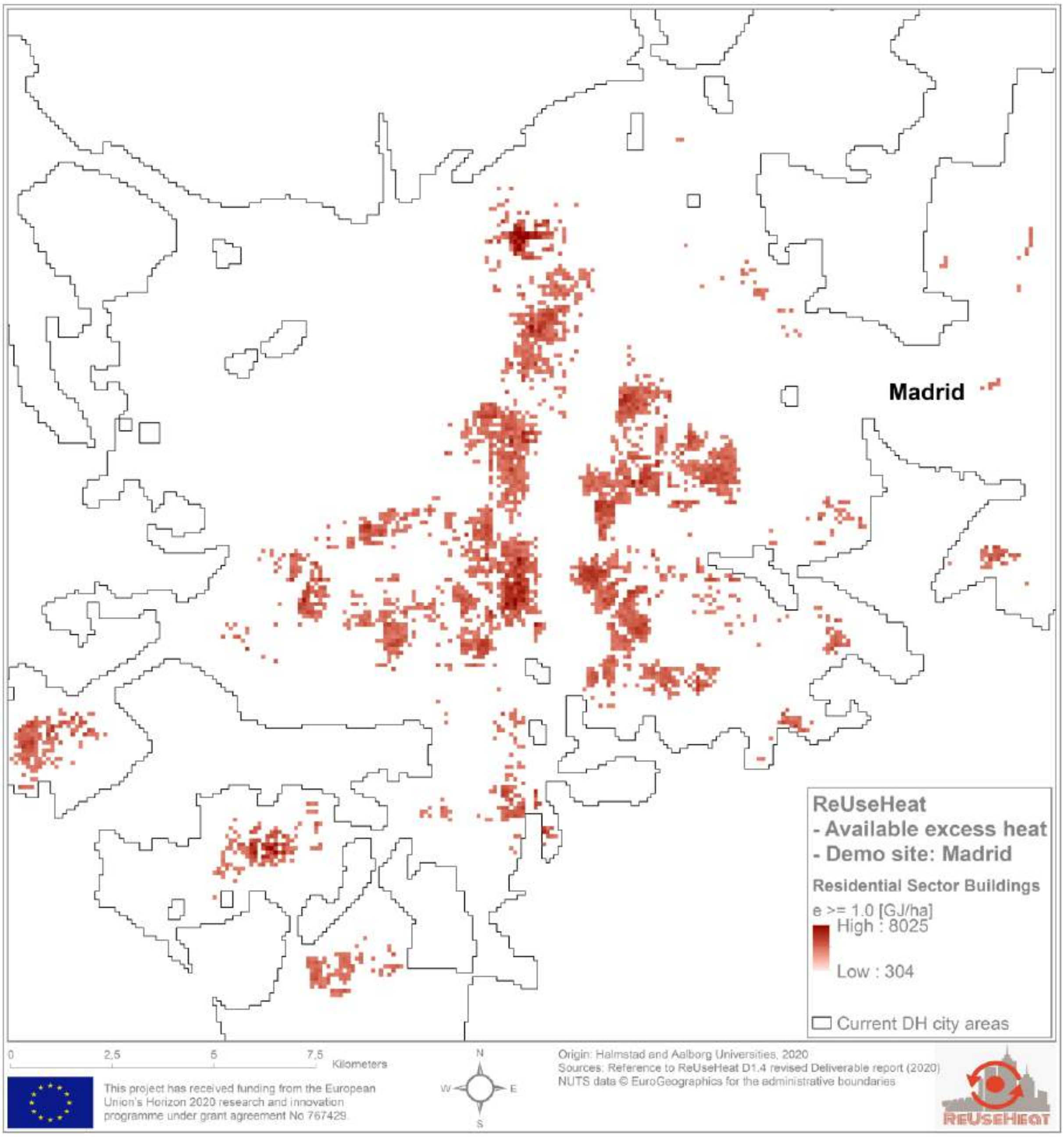

Figure 27. Available excess heat by hectare for residential sector buildings in extracted grid cells with plot ratio values, e, at 1 or above. Close-up of the Madrid city area (ES).

8.4 Comments

The main comment needed to make for this source category assessment is, to repeat, that there is no evidence underlying the assumption that residential buildings with plot ratio values at one or above are equipped with central cooling systems suitable for excess heat recovery. The actual distribution and character of cooling technologies used within this sector, particularly technologies that are suitable for large-scale heat recovery, is therefore an area apt for future studies. In this sense, the results from this study should be seen as indicative only. Another noteworthy comment is that Swedish building practises, which implicitly are reflected in the used benchmark data, may not be representative of those in other EU28 member states. This is consequently a model simplification which could be improved. Finally, to say that the residential sector, generally, is not a sector where to look for excess heat recovery opportunities, should perhaps be re-evaluated. But for large-scale recoveries by district heating, cooling technologies which allow recovery must be installed.

9 Waste water treatment plants

The potentials for heat recovery from urban waste water treatment plants, a.k.a. sewages, have been established here based on the fundamental condition that external heat – in principal – never (or only in exceptional cases, e.g. Artic conditions) is added to sewage plant treatment processes. The major significance of this is that it is fair to assume that the heat content present in post-treatment sewage water should equate approximately to heat volumes designated for hot water preparation in residential and service sectors. Given some partial in-blend of so-called "day-water", i.e. rainwater, it may also follow that a certain degree of cooling of the total volume of incoming sewage water takes place.

When realising the large count of urban waste water treatment plants currently operating in city vicinities throughout the European continent, here anticipated at some 23,200 facilities in all, the future prospects for heat recoveries from this source category appears as quite massive. Albeit there are no coherent records, in the EU28 context, as of how much heat is currently being recovered from these facilities, it is likely that very little of the current potential is utilised. However, the concept of excess heat recoveries from sewages is attracting increasing interest, as indicated among others by Schmid [43]. In terms of dedicated potential estimates, Neugebauer et al. [42] presented a study in 2015 addressing the Austrian context, and, more recently, the potential for waste water excess heat recoveries by means of district heating systems in Hungary was assessed by Somogyi et al. in [44].

Since urban waste water management is regulated in EU28 by the so-called "Wastewater Directive" [215], by which all facilities with design capacities (DC) above 2000 p.e. (person equivalents) are obliged to report annually, a comprehensive repository of facility data has been assembled over the last 25 years. Appropriate for studies such as this, these data compilations are publicly available at the European Environment Agency (EEA) in Copenhagen, where, for this assessment, the 2014 Waterbase-UWWTD_v6 dataset has been used [216]. By successive monitoring and follow-up, thus, to evaluate the progress by which member states manages to implement directive statutes, e.g. improved water quality in rivers, lakes, and seas, a series of reports have been published by the European Commission. The latest of these publication, the ninth report, summoning the progress made by year 2014, is used here for reference [217].

As will be further presented below, the main approach used to assess available excess heat from this source category involves first of all the above mentioned Waterbase-UWWTD_v6 dataset, which was subjected to a selective process by which to extract only operational EU28 facilities. Secondly, since in this dataset, apart from geographical coordinates, load capacities are given, a linear regression model was built wherein such capacities constitute independent variables. Next, as input data for the model, a compilation of time-series data was assembled from 20 Swedish district heating operators that utilise available excess heat from sewage water in large-scale compressor heat pumps, essentially on the basis of statistics from the Swedish District Heating Association (SDHA), for references, see section 9.2.2 below. Complementary to this, corresponding time–series data on load capacities from the 20 sewage facilities associated to these district heating operators, was assembled from yearly environmental reports whereby correlations between load capacities and recovered excess heat volumes could be established.

With respect to load capacities, it may further be mentioned here that such capacities for waste water treatment plants in EU28, commonly given by the unit person equivalent (p.e.), as stated above, may be determined by two similar measurements. As one person equivalent regularly means "the organic biodegradable load having a five-day biochemical oxygen demand (BOD_5) of 60 grams of oxygen per day", a few European countries (Sweden, Norway, and Lithuania), uses instead the BOD_7 measure. By the latter, one p.e. is defined as "the organic biodegradable load having a seven-day biochemical oxygen demand (BOD_7) of 70 grams of oxygen per day", however, since the two measures are compatible and principally equivalent, no further distinction has been made between the two in this work.

Load capacities may, as briefly mentioned above, further be given as design capacity (DC), which refers to nominal plant capacities, and by load entering (LE), which denotes the actual, measured pollution load of incoming sewage water over a one-year period. Both of these capacity metrics are given in the Waterbase-UWWTD_v6. In terms of temperature levels of sewage water, an annual average temperature of 12°C for treated waste water flows is 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 3 above), and seldom to decrease below this value (in summer times however, likely to occasionally be higher).

9.1 Methods

The methods used here to arrive at the available and accessible excess heat potentials from urban waste water treatment plants, is a combination of approaches utilising, on the one hand, experience-based correlations between found load entering values and available excess heat from model input data, and, on the other hand, benchmark values for domestic hot water energy demand. In addition, the approach includes, as for all considered source categories, the element of spatial analysis, whereby the locations of operational sewage plants and their geographical coherence with and to current district heating areas, are assessed by means of a GIS.

Table 40. Heat demands for residential (RES) and service (SER) sector domestic hot water preparation, and for low-temperature industrial process heat (IND, process heat below 100 °C) for EU28 member states. Source: [218]

MS	Q_{tot} (RES & SER) (PJ)	Q_{DHW} (RES) (PJ)	Q_{DHW} (SER) (PJ)	Q_{DHW} (RES &SER) (PJ)	Q_{DHW} (IND) as PH <100 (PJ)	Q_{DHW} (RES, SER & IND) (PJ)
AT	232	26	5	31	14	46
BE	324	29	7	37	26	63
BG	69	11	1	12	17	29
CY	9	3	1	4	0.1	4
CZ	237	30	4	35	22	56
DE	2413	318	54	371	197	569
DK	167	24	3	26	11	38
EE	34	3	0.4	3	2	4
EL	120	23	2	26	6	32
ES	471	156	16	172	12	184
FI	226	12	4	16	30	46
FR	1514	106	45	151	39	189
HR	69	8	1	9	6	15
HU	210	12	5	17	14	31
IE	105	13	2	15	4	19
IT	1277	140	37	177	94	271
LT	46	6	1	6	9	15
LU	26	1	1	2	0	2
LV	46	5	1	5	2	8
MT	3	0.3	1	1	0.0003	1
NL	425	38	11	49	54	103
PL	658	62	8	70	60	130
PT	62	21	5	27	13	40
RO	183	22	3	26	19	44
SE	296	33	5	38	15	53
SI	39	6	1	6	2	8
SK	96	10	2	12	5	17
UK	1360	212	35	246	49	295
EU28	**10718**	**1330**	**259**	**1589**	**723**	**2311**

As for the benchmark value for domestic hot water energy demand, the comprehensive estimates performed by Fraunhofer ISI in WP3 of Heat Roadmap Europe project, referring to residential, service, and industry sectors of the EU28 member states, was made available and used in this study [218]. As presented in Table 40, the total 2015 heat demand in EU28 residential and service sectors (delivered energy demand) for domestic hot water preparation amounted to 1.59 EJ. Industrial process heat demands below 100°C were correspondingly assessed to some 0.72 EJ, which would indicate a total demand volume of approximately 2.3 EJ for these purposes. The main benchmark, i.e. the residential and service sector total, as well as that constituting the total sum of this and low-temperature industrial process demands, are included in Figure 29 below.

Here, it should be noted that no distinction has been made with reference to ordinary load (that is, incoming sewage flow from residential and service sectors), and that of industrial load in this work. The share of industrial load is generally only marginal, but it may be significant at certain facilities. However, as industrial loads are characterised by relatively higher specific pollution concentrations per water flow volumes (compared to ordinary load), this neglect is considered less significant for the study outputs since available excess heat primarily is determined by water flow volumes and not by its concentration level of pollutants. In this particular respect, further, no direct attention has been paid to the fact that incoming sewage water regularly also consists of in-blended “day-water” (as it is called in Swedish, i.e. rain etc.). Indirectly however, this factor is considered in the evaluation of modelled excess heat volumes by relating them to the used benchmarks.

As for the temporal dimension, seasonal and location-based variations in heat demand magnitudes are considered by use of the European Heating Index (EHI), see for example Werner [47, 219]. This index is based on heating degree day numbers and, since the regression model outputs refer to Swedish conditions, the index was transformed into a factor by which to compensate for this effect. The factor itself was established by dividing found EHI values of any given facility (derived from a square kilometre EHI raster grid) with the average EHI value of the 20 Swedish model input data locations (115.82). Hereby, the Nordic heating season character of the used Swedish model input data was neutralised and thus applicable for the assessments of the entire population of EU28 sewage facilities. The significance of incorporating the EHI factor in the modelling is that, irrespective of the magnitude of excess heat available for recovery from a given sewage plant, the prospect of utilising this heat is determined by the presence of building heat demands to be satisfied by the recovered heat.

With regards to the spatial dimension, the UMZDH-layer dataset has been used also for this source category, where, for the presentation in this report, the “inside or within 2 kilometre”-criteria (from current urban district heating areas), constitute the preferred choice.

9.2 Data

In this section, the two main datasets used in this assessment, i.e. the EEA Waterbase-UWWTD_v6 dataset and the model input data assembly, together with a more detailed account of the linear regression model, are presented in named order.

9.2.1 Urban waste water treatment plants (EEA)

In the Waterbase-UWWTD_v6 dataset [216], the table “T_UWWTPS” refers to the data year 2014 and holds all together 30,437 records of European urban waste water treatment plants (including also CH, IS, and NO). From this total count, a selection process was performed, removing e.g. closed and non-operational plants, plants with erroneous geographical coordinates, overseas or Atlantic facilities (FR, ES, and PT), and finally by EU28 membership. The final selection, thus referring to anticipated operational EU28 plants, counts 23,189 plants, all for which geographical coordinates are present.

Apart from various metadata, such as plant names, ID’s, country codes etc., the table includes key information on design capacities and load entering for the reporting year. For two countries, Croatia (HR) and Sweden (SE), capacities are only given as design capacities, for one country (Finland (FI)) the reverse is the case (i.e. only reports on load entering). To correct this, the average ratio (73.7%) between load entering and design capacities for the 24 EU28 member states with correctly reported data in both categories (ES was excluded here due to 255 design capacity reports mistakenly stating "9 999 999"), was used to assign calculated capacities in these instances. An overload indicator was further introduced signifying instances where entering load values was found at a factor 1.2 above reported design capacity values. In all, 1602 such instances were found, and for factors reaching above 2.0, corrected load entering values were established by relating the EU28 average LE/DC ratio to reported design capacity values. Table 41 presents the final study selection with corresponding design capacities divided by five classes for all of the EU28 member states.

Table 41. Study selection of urban waste water treatment plants from the Waterbase-UWWTD_v6 dataset, by five design capacity classes (kp.e.) during 2014 for the member states of EU28. Source: [216]

MS	**1. < 2**	**2. 2 – 9.9**	**3. 10 – 49.9**	**4. 50 – 99.9**	**5. > 100**	**Total [n]**
AT	1	352	210	35	36	634
BE	28	185	148	24	17	402
BG	1	14	54	18	17	104
CY		7		3	5	15
CZ	37	370	137	31	25	600
DE	46	1964	1664	322	248	4244
DK	1	176	103	34	29	343
EE	8	25	16	1	7	57
EL		36	88	22	13	159
ES	64	1046	585	136	189	2020
FI	1	58	66	16	22	163
FR	83	2271	924	187	145	3610
HR	4	30	29	11	7	81
HU	261	303	131	25	27	747
IE	13	87	47	12	8	167
IT	895	1739	919	215	185	3953
LT	2	28	33	3	9	75
LU	3	15	8	6	1	33
LV	22	36	25	2	4	89
MT			1	1	2	4
NL	2	62	150	65	58	337
PL	204	842	399	123	97	1665
PT	4	269	126	29	39	467
RO	172	210	114	21	39	556
SE		236	138	35	23	432
SI	17	41	21	7	5	91
SK	57	112	62	17	15	263
UK	15	943	613	126	181	1878
Total	**1941**	**11457**	**6811**	**1527**	**1453**	**23189**

From this table it may be concluded that a majority of European urban waste water treatment plants are smaller installations (second class), and mid-sized facilities (third class), serving smaller towns and cities. More than half of the total population of plants (57.8%) have design capacities below 10,000 person equivalents, while only 6.3% represent large city installations with design capacities above 100,000 p.e.

According to the ninth implementation report mentioned above [217], the total load entering some 23,500 EU agglomerations in 2014 reached 604 million p.e., while it is also stated that the total "installed treatment capacity in the EU", i.e. the total design capacity, represents about 780 million p.e. These number are well in harmony with those assessed here, where the total load entering, after adjustments, was found at 558.6 million person equivalents, at a corresponding total EU28 design capacity of 779.7 million p.e.

9.2.2 Model input data

A compilation of time-series data from 20 Swedish district heating operators that utilise available excess heat from sewage water in large-scale compressor heat pumps, was assembled on the basis of statistics from the Swedish District Heating Association (SDHA) [220-222], and information from some other additional sources [223-227]. Complementary to this, time–series data on plant capacities, flows, pollution loads etc., from 20 corresponding Swedish sewage facilities, was assembled from yearly environmental reports, here referenced in bundle [228-276], on which basis the model input data assembly was built.

Table 42 presents the 20 Swedish systems by plants names, city names, and district heating operator names (where found, otherwise city or municipality names), as well as average time-series load entering (LE) values gathered from plant environmental reports and nominal design capacity (DC) values as reported in the Waterbase-UWWTD_v6 dataset. For comparison, the average LE/DC ratio of the total sum for the 20 Swedish systems was found at 71.7%, which is in fair agreement with the EU28 average ratio value.

Table 42. Sewage plant names, city names, district heating operators, load entering (LE), and design capacities (DC), for the 20 Swedish cities and urban wastewater treatment plants used for the model input data assembly. Design capacities are those reported by EEA and load entering are average values from time-series data collected from available plant environmental reports mainly between the years 2013 to 2017

UWWTP's by LE Class (city and DH operator)	**LE [p.e.] (plant reports)**	**DC [p.e.] (UWWTP, 2014)**
3. (10 000 - 49 999 p.e.)	**88455**	**124000**
Granskars avloppsreningsverk (Söderhamn)	14500	22500
Hammargards arv, Kungsbacka (Statkraft Värme AB)	39455	52000
Oskarshamns ARV, Ernemar (Oskarshamn Energi AB)	19500	25000
SALA/Heby ARV (Sala-Heby Energi AB)	15000	24500
4. (50 000 - 99 999 p.e.)	**437884**	**790000**
Borås avloppsreningsverk, Gasslosa (Borås Energi)	73000	110000
Källby avloppsreningsverk, Lund (Kraftringen AB)	86233	120000
KALMAR ARV, Tegelviken (Kalmar)	66236	100000
ONS AVLOPPSREN VERK (Umeå)	85500	200000
Simsholmens ARV (Jönköpings kommun)	59244	95000
Smedjeholms ARV (Falkenberg)	67671	165000
5. (> 100 000 p.e.)	**3057016**	**4086000**
BROMMA RENINGSVERK, Stockholm (Norrenergi AB)	235250	400000
Ellinge Avloppsreningsverk, Eslöv (Ringsjö Energi)	103500	330000
Eskilstuna Avloppsreningsverk (Eskilstuna)	108424	130000
Gryaab AB Ryaverket, Göteborg (Göteborg Energi)	844360	959000
HENRIKSDALS RENINGSVERK (Fortum Värme AB, Stockholms stad)	865000	1000000
KUNGSANGENS RENINGSVERK, Västerås (Mälarenergi AB)	106272	137000
Oresundsverket, AVR, Helsingborg (Öresundskraft AB)	158815	200000
Sjölunda Avloppsreningsverk, Malmö (E.ON Värme Sverige AB)	362385	550000
Skebacks Avloppsreningsverk, Örebro (HÖK)	115843	180000
Uppsala Avloppsreningsverk (Uppsala)	157167	200000
Grand Total	**3583354**	**5000000**

With respect to the sewage plant time-series data, there occurred no reason to question its representativeness as reflecting normal, characteristic operational conditions. With reference to the district heating operator time-series data, however, the assembled data showed in a few instances some deviances and irregularities that might indicate altered operational conditions between different years. In one such case (city of Malmö), the heat pump operation appears to have been shut down in 2009, where after reported volumes are but fractional compared to those reported prior to the operation closure. Another instance refers to used electricity and heat output reported for Fortum Värme AB (Henriksdals reningsverk, Stockholm), for which the SDHA statistics appear to include data from heat pumps utilising as well other heat sources (e.g. lake water and low-temperature industrial excess heat). By consulting alternative statistical sources, in this case [225], more accurate information was gathered with respect to used electricity and heat output from this, the largest, of the model systems.

From these considerations, three different time-series datasets have been elaborated in the modelling, as presented in Table 43. In the first (No. 1), all time-series data is included as found (totalling at 193 data years). It is noticeable here how the influence from what is likely exaggerated values reported for the Fortum Värme AB operation, as mentioned above, significantly increases electricity and heat volumes.

Table 43. Model input data time-series datasets from 20 Swedish district heating operators utilising processed sewage water as heat input (Q_L) for compressor heat pumps (electricity used (W)), to generate annual heat outputs (Q_H). Data mainly from the Swedish District Heating Association (SDHA) from start-year 2005 to end-year 2016. Practical COP and "Full operation hours" refer to average values

No.	Description of time-series dataset	DH systems [n]	Data years [n]	QL [TJ/a]	W [TJ/a]	COP [-]	QH [TJ/a]	Full op. hours [h]
1	All data as found	20	193	10103	4533	3.03	14637	2824
2	Characteristic data years	20	170	6725	3050	3.03	9775	2615
3	Characteristic data years – systems with uncertain data removed	18	159	5263	2400	3.01	7662	2553

In the second time-series dataset (No. 2), all 20 systems are still included, albeit less characteristic yearly reports have been omitted. In the case of the abovementioned Henriksdals reningsverk in Stockholm Stad, the SDHA data has been completely replaced by the Hammarbyverket statistics [225], among some minor corrections for a few other systems, which accordingly results in somewhat lower total volumes.

In the third case (No. 3), two systems (Malmö and Gothenburg) has been excluded from the No. 2 dataset, partly due to operational closure (Malmö), partly due to non-representative volumes in relation to reported design capacity and load entering values. The latter adjustment was a result also of testing different selections in the attempt to obtain better overall fitting of anticipated regression functions in relation to benchmark domestic hot water energy demand volumes.

9.2.3 Linear regression model

By linear regression modelling, describing the correlation between experience-based load entering values and corresponding recoveries of available excess heat at the 20 model systems, six regression functions (R1 to R6) were elaborated in this assessment. For the record, it should be mentioned that the model has been constructed so as to be re-run at the occasion of new, additional data (the provision of which, by the way, is one of the objectives of the ReUseHeat T1.1 online survey). The six regression lines, and the corresponding input model data points, are presented for the load entering interval between zero and one million person equivalents in Figure 28.

Three of these functions (R1, R3, and R5) are set to have their intercept at zero, while the three others (R2, R4, and R6) are not. As presented in Table 44 below, R1 and R2 utilises the time-series dataset No. 3, R3 and R4 refers to dataset No. 2, while R5 and R6 refers to dataset No. 1. The differences between the three datasets are clearly visible in Figure 28, where dataset No. 1 (R5 and R6, in blues) produces "high" estimates, dataset No. 2 (R3 and R4, in yellows) renders "low" estimates, while dataset No. 3 (R1 and R2 in reds), generates "mid" estimates.

If extending the six functions to the EU28 context, where found load entering values from the Waterbase-UWWTD_v6 dataset amount to 558.6 million person equivalents, and if here introducing the domestic hot water benchmark values from Table 40, as in Figure 29, it is clear that dataset No. 2 (R3 and R4) arrives at the most conservative approximation.

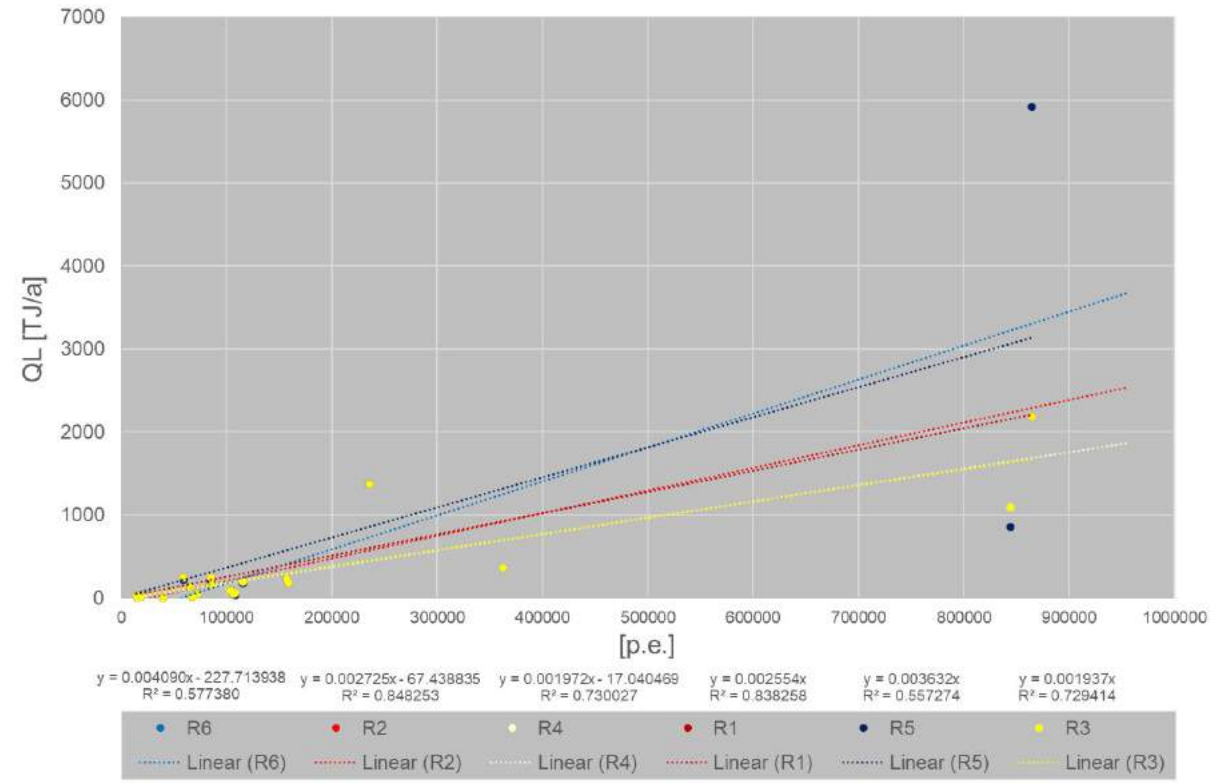

Figure 28. Six linear regression functions (R1 to R6) by correlation between time-series data on load entering (p.e.) and heat input (Q_L) for compressor heat pumps from the three model datasets. Interval below one million p.e.

At a EU28 load entering value of 558.6 million person equivalents, both of these regression lines (R3 and R4) anticipate available excess heat volumes in the order of 1.0 EJ, which constitute roughly 63% of the residential and service sector benchmark energy demand.

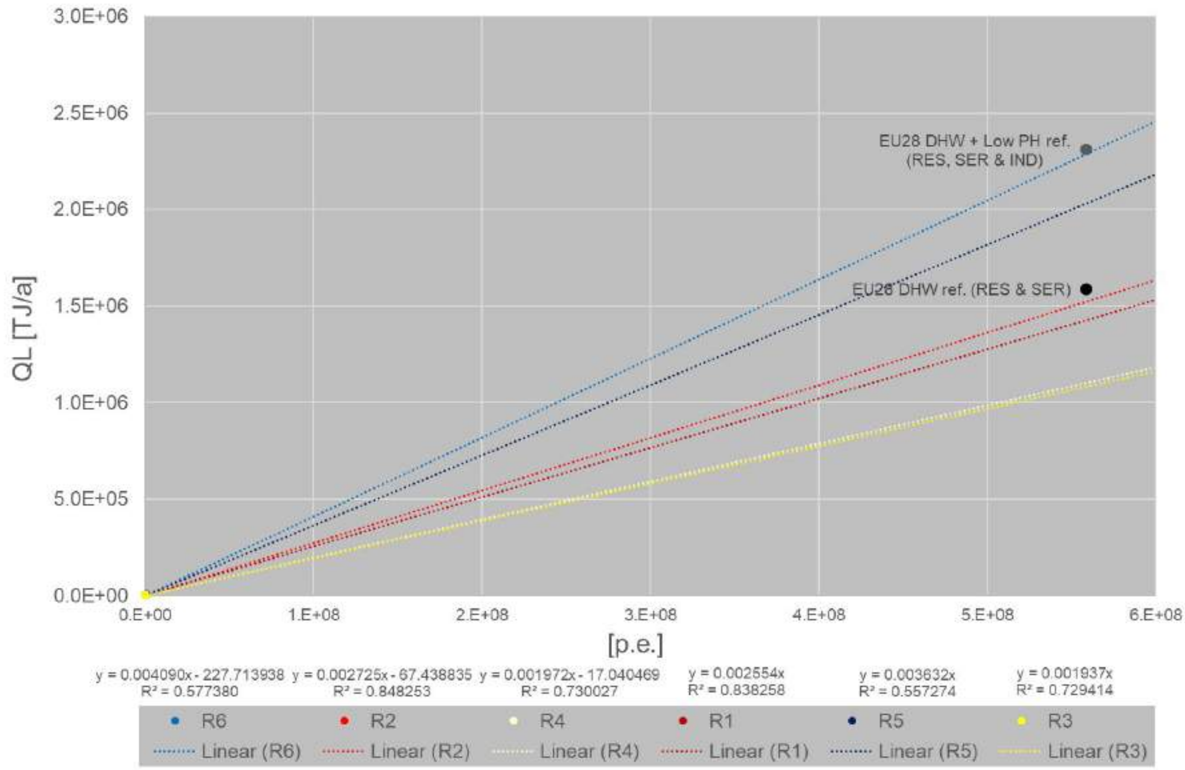

Figure 29. Six linear regression functions (R1 to R6), by correlation between time-series data on load entering (p.e.) and heat input (Q_L) for compressor heat pumps from the three model datasets, extended to found EU28 data on total load entering (2014) and domestic hot water demand (2015) in residential and service (RES & SER), and industrial (IND) sectors.

If, on the contrary, narrowing the load entering interval down to values below one hundred thousand person equivalents, it becomes evident that it is mainly here, in this lower load entering register, that the impact of the different regression characteristics becomes decisive. By analysis of the model input data, a clear majority of European sewage plants was found in this lower register: 90.7% of all studied facilities reported load entering values below 50,000 person equivalents in 2014.

In Figure 30, this lower load entering register is highlighted for the three regression lines R2, R4, and R6 (none of which have their intercept set to zero). In comparison to R1, R3, and R5, the main benefit of these three regression lines are their tendency not to overestimate available excess heat at these low registers. However, since they do not intercept at zero, they are in need of support functions (all linear, originating in origo) to anticipate reasonable correlations at load entering values below 50,000 p.e.

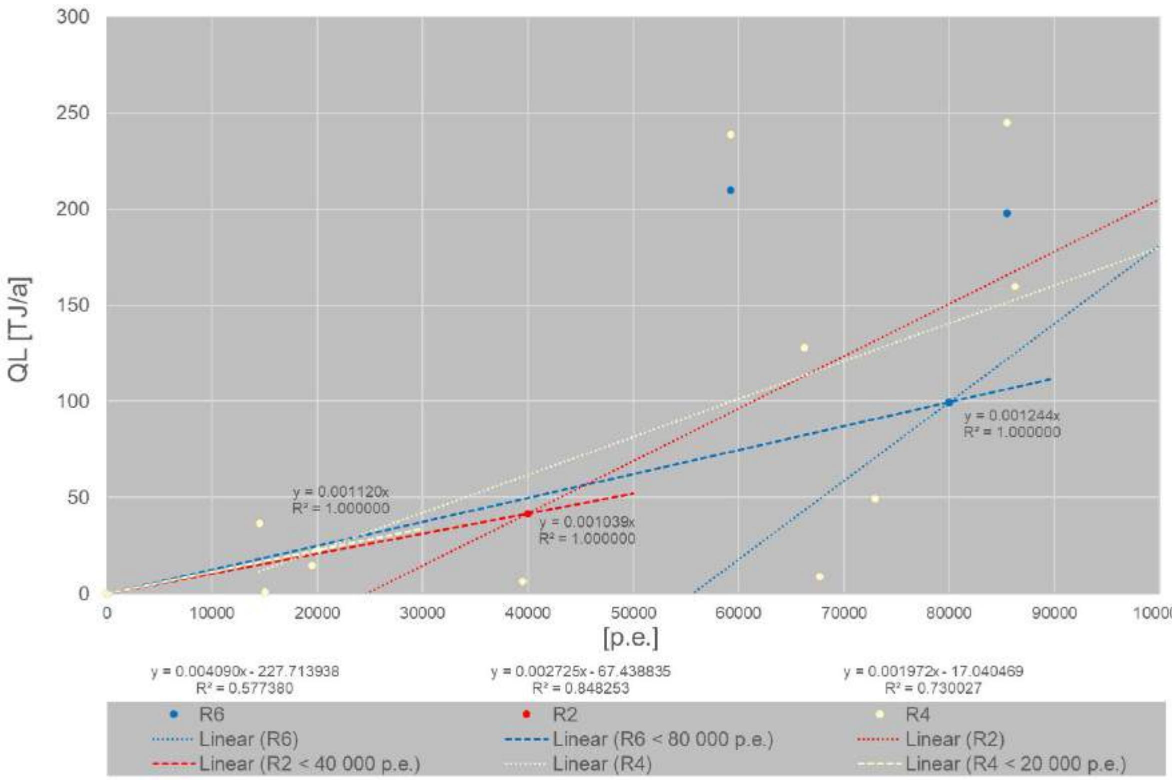

Figure 30. Illustration of R2, R4, and R6 function characteristics at low load entering values (p.e.). Linear support functions originating in origo are introduced to compensate for negative estimates and to anticipate reasonable dependent variable results at load entering values below 50,000 p.e.

As can be seen in Figure 30, the R4 function manages to maintain the original correlation all the way down to 20,000 person equivalents, while both R2 (40,000 p.e.) and R6 (80,000 p.e.) are in need of complementary linear support functions at these load entering values not to underestimate low register potentials. Another important feature of R4, in comparison to the other two, is that it manages to stipulate highest shares of available excess heat in the critical load entering interval between 20,000 to 60,000 person equivalents, while simultaneously avoiding generating overestimations at higher load entering values.

To provide further evidence of the general suitability of regression function R4, all six regression functions were applied to the 20 model input data systems (load entering values), in a validation and comparison process. By this procedure, a basis for evaluating the appropriateness of each function was provided, as shown in Figure 31 below, in which it may be observed that the R4 function constitutes the best possible fit to the model systems, considering all three load entering classes representative of these 20 model systems.

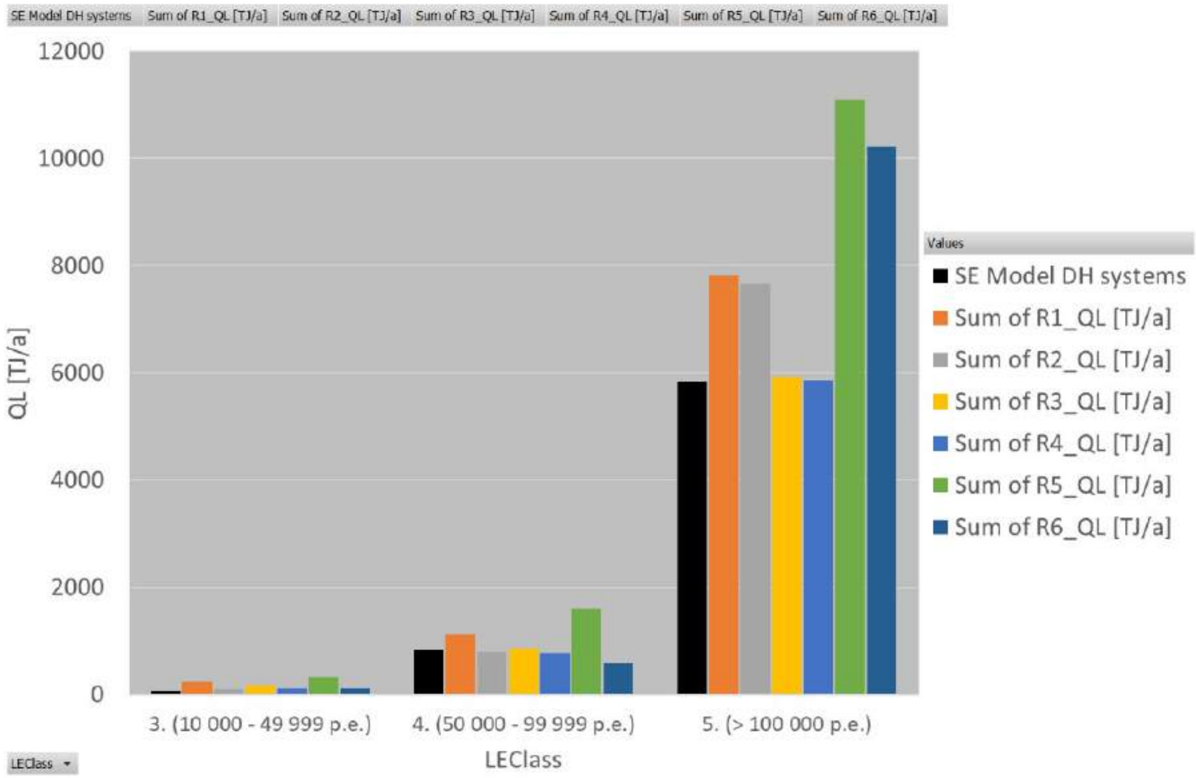

Figure 31. Validation and comparison of the six regression functions (R1 to R6) by application to the 20 Swedish model systems (load entering values), where the model system volumes refer to dataset No. 2. Actual volumes of available excess heat recovered in the 20 model systems (in black staples), and modelled volumes for each regression function.

From this analysis, a decision was taken which resulted in the selection of regression function R4 as representing the most suitable estimation upon which a moderate and conservative potential assessment of currently available excess heat from EU28 urban waste water treatment plants may be made. All here reported results for this source category is consequently based on the R4 function predictions. However, results have been generated for all six functions, albeit not accounted for here.

In summary, the six regression functions and their corresponding characteristics are presented in Table 44. As can be seen, the R1 and R5 functions are conceived to overrate available excess heat potentials at all considered load entering classes, while function R6 is conceived to do so only in the higher load entering segment. R2 displays the best fit at below 50,000 person equivalents, but overestimates at above 100,000 person equivalents. Function R3 is considered the second-best fit among the six functions, however, slightly overrating the potentials in the lower load entering segments.

Table 44. Characteristics of the six regression functions and references to used model time-series datasets and comments on suitability for the modelling of available excess heat potentials

Label	Dataset used	Main function	R^2	Support function	Comment (application to model systems)
R1	3	y = 0.002554x	0.838	Intercept at origo	Overrate at all LE classes.
R2	3	y = 0.002725x - 67.438835	0.848	y = 0.001039x (x<40k p.e. (LE))	Best fit at LE <50k. Overrate at LE >100k.
R3	2	y = 0.001937x	0.729	Intercept at origo	Overrate at LE <50k, otherwise fair.
R4	2	y = 0.001972x - 17.040469	0.730	y = 0.001120x (x<20k p.e. (LE))	Slight overrate at LE <50k, otherwise fair.
R5	1	y = 0.003632x	0.557	Intercept at origo	Significant overrate at all LE classes.
R6	1	y = 0.004090x - 227.713938	0.557	y = 0.001244x (x<80k p.e. (LE))	Fair at LE <100k, significant overrate >100k.

9.3 Results

The resulting excess heat potentials for EU28 urban waste water treatment plants are presented in this section mainly in the form of maps and tables. As for the former, regarding available excess heat from all 23,781 modelled systems, a first image is presented in Figure 32, while the corresponding national potentials are presented in Table 45 below.

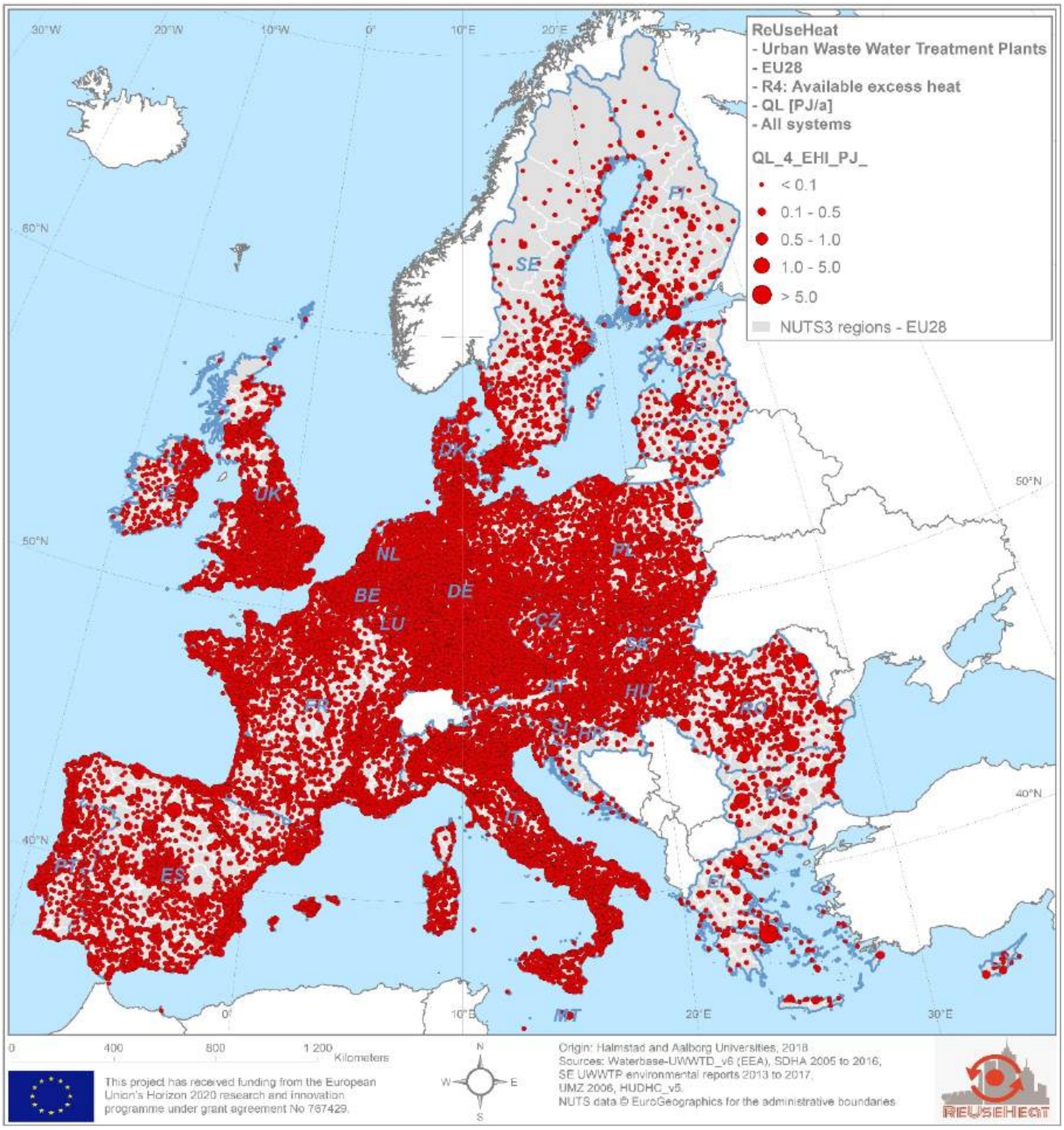

Figure 32. Available excess heat from 23,189 EU28 urban waste water treatment plants, according to regression function R4.

In this map, the immense presence of waste water treatment plants, distributed quite homogenously among the 28 member states, is highly visible. Since most of these systems, by definition (being *urban* waste water treatment plants) and given their common objective of providing water management services mainly to human population centres, are located in vicinity to urban areas, the prospects of recovering heat from this source category must be considered beneficial, if not by other, so at least, by means of geographical coverage.

In terms of numbers, the total EU28 available excess heat potential from all systems, as conservatively assessed by the R4 function, amounts to 763 PJ annually, as detailed in Table 45. For reference, the R6 function, representing the other (high) end of the modelling spectra, suggests a total of 1069 PJ, which may provide an indication as of the range within which the modelling outputs were found. In Table 45 are also included, for reference, average national EHI values, where, as expected, Belgium represent the index value 100, and the overall EU28 average value is found at 95.

Table 45. Available and accessible excess heat from urban waste water treatment plants in EU28. All systems.

MS	UWWT plants [n]	EHI (average)	QL (R4) [PJ]	QH (R4) COP 3.0 [PJ]
AT	634	104	20.7	31.1
BE	402	100	11.6	17.4
BG	104	97	7.7	11.6
CY	15	94	1.1	1.6
CZ	600	109	14.1	21.2
DE	4244	106	165.8	248.8
DK	343	109	11.2	16.9
EE	57	121	2.3	3.4
EL	159	70	11.2	16.8
ES	2020	72	64.2	96.3
FI	163	129	12.0	17.9
FR	3610	91	90.5	135.7
HR	81	90	4.0	6.1
HU	747	101	13.5	20.2
IE	167	97	6.6	10.0
IT	3953	78	81.0	121.5
LT	75	116	4.4	6.7
LU	33	102	1.0	1.5
LV	89	118	2.2	3.3
MT	4	53	0.4	0.6
NL	337	100	26.8	40.2
PL	1665	111	54.5	81.7
PT	467	67	11.0	16.6
RO	556	105	17.5	26.3
SE	432	119	16.5	24.7
SI	91	98	2.2	3.3
SK	263	106	5.5	8.2
UK	1878	98	103.3	155.0
EU28	**23189**	**95**	**763.0**	**1144.5**

As for the accessible excess heat potential, given in Table 45 for all systems at a practical COP of 3.0 only in an indicative sense, since a majority of these facilities are located out of reach from current district heating systems, 1.14 EJ could at most be derived by use of heat pumps from all considered locations. The actual accessible excess heat volume, when subjected to the default study spatial restraint of being inside or within 2 kilometres of current district heating city areas, however, is significantly lower.

As illustrated in the corresponding EU28 map in Figure 33, and as is further specified in Table 46 below, the total number of plants that meet this condition is reduced to 3982 instances, at which the sum of available excess heat now is found at the more moderate total of 417 PJ per year. Noteworthy, while this volume of available excess heat constitutes 55% of the full potential, the share of plants represent only 17% of the total population. A preliminary conclusion from this observation may be that, by applying the spatial restraint, mainly smaller plants are excluded, while larger plants (serving larger agglomerations) contribute in a higher degree to the found total. In a European context, an alternative explanation may further be that current district heating systems mainly are present in larger urban areas.

For a country like Germany for example, for which a close-up map for accessible excess heat potentials under given conditions is given in Figure 34, the drastic reduction of considered plants by this manoeuvre, a drop from 4244 to 418, provides an illustration of a phenomenon which may be observed for several other EU28 member states where district heating technologies have yet to reach fully mature deployment levels. The mentioned preliminary conclusion, that essentially only large agglomeration sewage plants remains after applying the spatial restraint, becomes quite apparent in this map.

For a country like Sweden, on the other hand, with comparably high presence of district heating areas, relatively speaking, as derivable from Table 5 above, available excess heat volumes under the given restraint amount to 13.5 PJ annually, a volume which constitutes as much as 82% of the total potential (16.5 PJ). From this it may naturally be concluded, although it should go without saying, that countries with higher deployment levels of district heating are in a position whereby their prospects to realistically recover and utilise excess heat from, not only, sewages but from any of the investigated source categories, is absolutely increased.

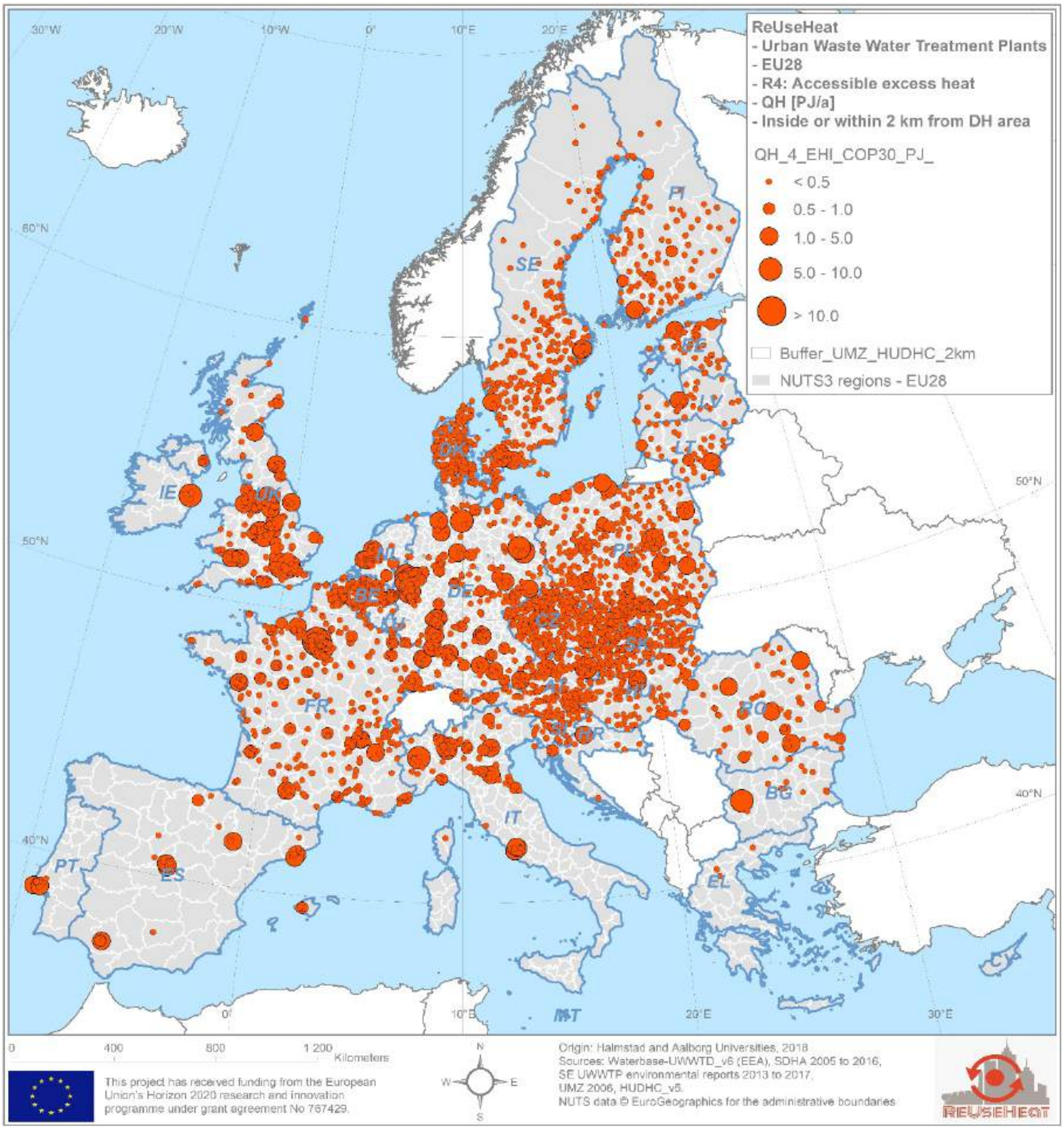

Figure 33. Accessible excess heat from 3982 EU28 urban waste water treatment plants located inside or within 2 km from urban district heating areas, according to regression R4, and at a practical COP of 3.0.

In complementary, it may also be said, that energy recovery from sewage plants, in general, is not entirely conditioned by current district heating deployment levels, only in so far as it concerns direct heat recoveries from sewage water. For all those locations around Europe void of such options, energy recovery from e.g. sewage sludge, represents an alternative means by which to improve the general energy efficiency of waste water treatment plants. By anaerobe digestion processes, the energy content inherent in sewage sludge may thereby be converted into gaseous fuels, which, used e.g. on-site for various purposes, may decrease the demand for other (external) energy supplies by fuel substitution.

Table 46. Available and accessible excess heat from urban waste water treatment plants in EU28, inside or within 2 kilometres of current urban district heating areas.

MS	UWWT plants (2km) [n]	QL (R4) (2km) [PJ]	QH (R4) COP 3.0 (2km) [PJ]
AT	231	15.9	23.9
BE	218	9.5	14.3
BG	13	4.0	6.0
CZ	369	13.2	19.8
DE	418	80.8	121.2
DK	199	9.7	14.5
EE	45	2.3	3.4
EL	3	0.2	0.3
ES	57	15.0	22.5
FI	106	8.1	12.1
FR	597	57.0	85.5
HR	12	2.7	4.0
HU	113	10.7	16.1
IE	6	4.0	6.0
IT	194	26.6	39.8
LT	33	3.4	5.1
LU	5	0.3	0.5
LV	35	2.0	3.0
NL	64	10.2	15.3
PL	445	44.5	66.8
PT	14	2.5	3.8
RO	76	12.1	18.2
SE	232	13.5	20.3
SI	42	1.3	1.9
SK	153	5.0	7.5
UK	302	62.1	93.2
Grand Total	**3982**	**416.6**	**624.9**

Under these given modelling conditions, it would certainly be fair to wonder what the corresponding available excess heat volume potentials are at the 10 km, 5 km, and completely within, spatial restraint criteria values also calculated under the spatial dimension mapping. The answers for such a question are that, for EU28 at the 10 km criteria, i.e. inside or within 10 kilometres of current urban district heating areas, some 507 PJ could be recovered from 8874 plants. By the 5-kilometre criteria: 460 PJ from 5875 facilities, and completely inside such areas: 393 PJ from a total of 1500 plants.

If assuming that the excess heat from these urban waste water treatment plants is recovered at the low-range temperature value of 8°C, see Table 3, and further relating this to an *ad hoc* annual average supply pipe temperature of 85°C for 3rd generation district heating systems, a theoretical COP value would be found at 4.7, thus indicating an average Carnot efficiency for this source category at 65%. At the conceived average sewage water temperature of 12°C, the corresponding numbers are 4.9 and 61%. In appendix 15.13, a complementary table with accessible excess heat volumes, inside or within 2 kilometres of urban district heating areas, at practical COP values of 2.5 and 3.5, respectively, is included for reference, see Table 68. Note also that all the considered 23,189 waste water treatment plants may be viewed as an operational layer in the PETA 4.3 web map [53].

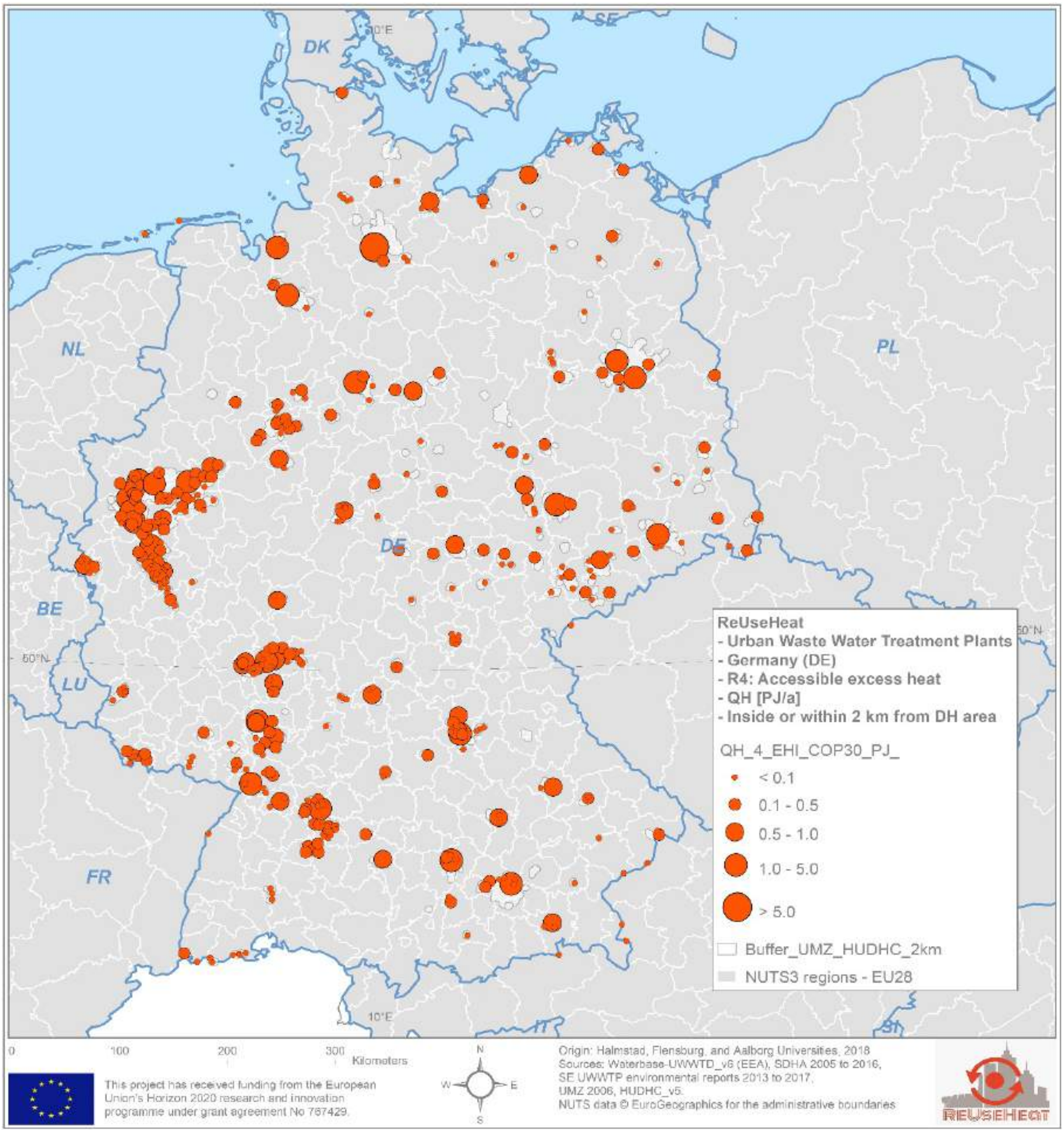

Figure 34. Accessible excess heat (Q_H) from 418 German urban waste water treatment plants located inside or within 2 km from urban district heating areas, according to regression R4 and at a practical COP of 3.0.

9.4 Comments

In view of this assessment, it should first be mentioned that the linear regression model used relies on the found correlation between annual volumes of recovered available excess heat (Q_L) and load entering (LE), at 20 Swedish model systems. For a study that aspires to project the correlations established by such a relatively small number of observations onto a significantly larger population, the availability of more input data by which to ascertain the sought relationship would certainly improve the quality of the modelling. Especially so by including data representative for the different climate conditions present in various parts of Europe. However, since the sought correlation is that between sewage plant load capacities and large-scale heat pumps used as heat sources in district heating systems, of which there appears to be a very limited set of real-world examples, such data is generally difficult to find. The operational experiences to be gained in the ReUseHeat Nice demo-site, is therefore expected to bring new valuable information in this respect.

With reference to the Waterbase-UWWTD_v6 dataset, which in all includes some 30,000 European urban waste water treatment plants, the made selection of anticipated operational EU28 facilities amounted in some 23,200 plants. It should be made clear, however, that, although comprehensively performed, this selection may still host a few closed or currently non-operational plants, as well as it clearly excludes more recent plants installed after the year 2014.

In general, when speaking about energy recovery from sewages, it would be negligent not to mention the considerable energy content “available” in sewage sludge. This was deliberately also mentioned above. In conclusion, still, it should be underlined that in many sewage plants already today, the recovery of such assets (preferably by anaerobe digestion processes to produce methane gas) is already standard practice. In terms of limitations regarding this report however, this aspect of energy recovery from sewages is omitted, since it is beyond the scope of the ReUseHeat Task T1.2 objectives.

10 Demo-sites

In this section, a brief account is given concerning the four demonstration cities (demo-sites) in the ReUseHeat project. For each site, a map illustrating the city area, and the four originally identified urban excess heat sources (including three conventional sources categories) within 20 kilometres of the city perimeters (UMZDH-layer definition), is presented together with some key metrics mentioned in the text. Note also that in this context, only available excess heat potentials are reported and referred to. The reason for this is that other modelling activities in WP1, e.g. T1.4, will perform more detailed modelling, by use of other techniques, to assess the accessible excess heat potentials at these four locations.

10.1 Brunswick (Data centres)

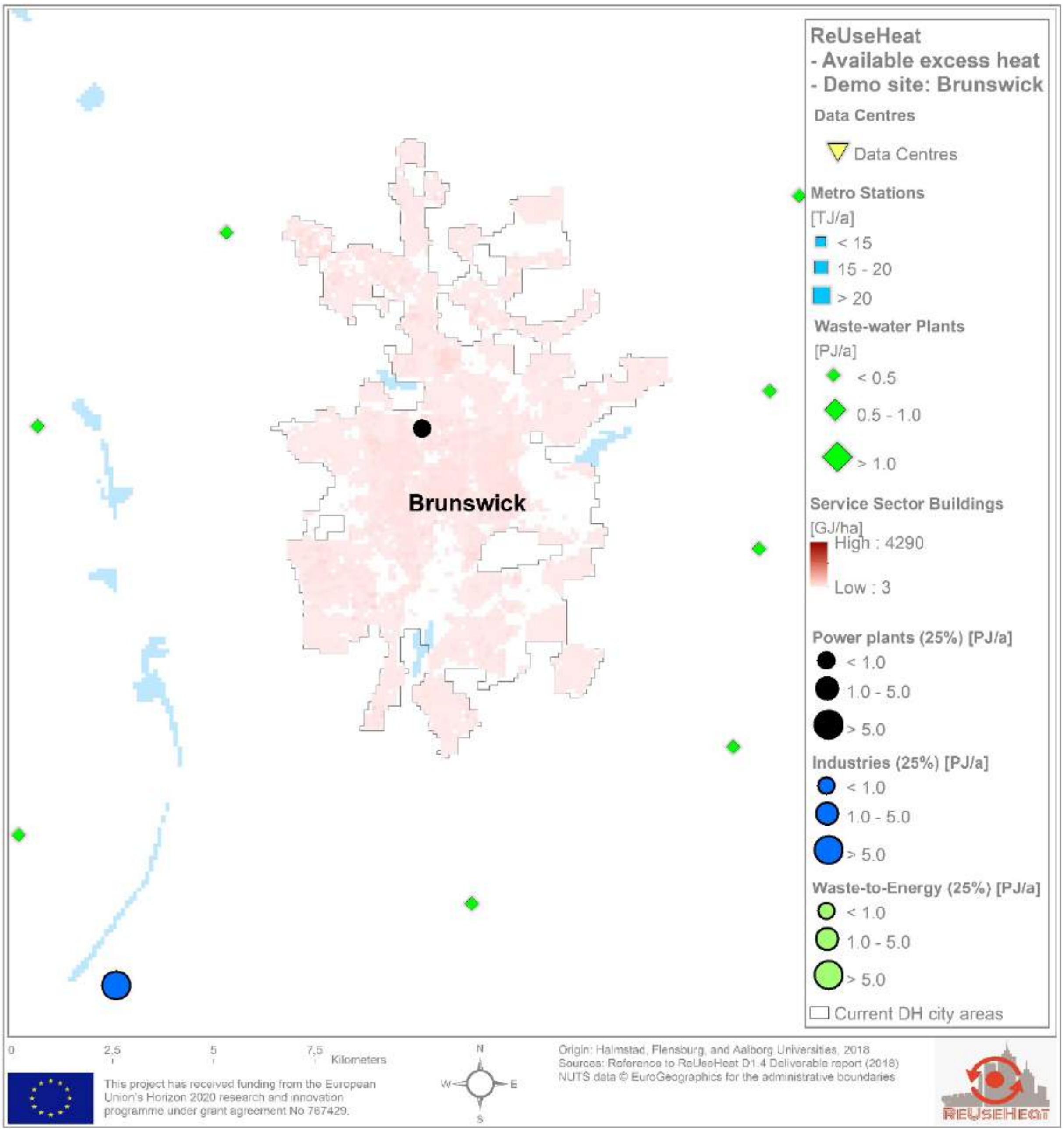

Figure 35. Available excess heat from unconventional and conventional urban excess heat sources in the demo-site of Brunswick (DE).

At the Brunswick demo-site, as outlined in Figure 35 and further summarised in Table 47 and Table 48 below, the total sum of available excess heat from all considered sources amounts to 13.6 PJ on a yearly basis. This heat is available from a total 31 activities, mainly so from 27 waste water treatment plants (1.2 PJ) and four conventional sources (12.2 PJ, at 25% of maximal theoretical potential), and to a lesser extent from service sector buildings (0.1 PJ). The source category to be demonstrated in Brunswick is a data centre, which, according to the used datasets, appears to be first of its kind since there are no current records of such operations. According to the used data, further, there is no metro system in Brunswick.

10.2 Bucharest (Metro stations)

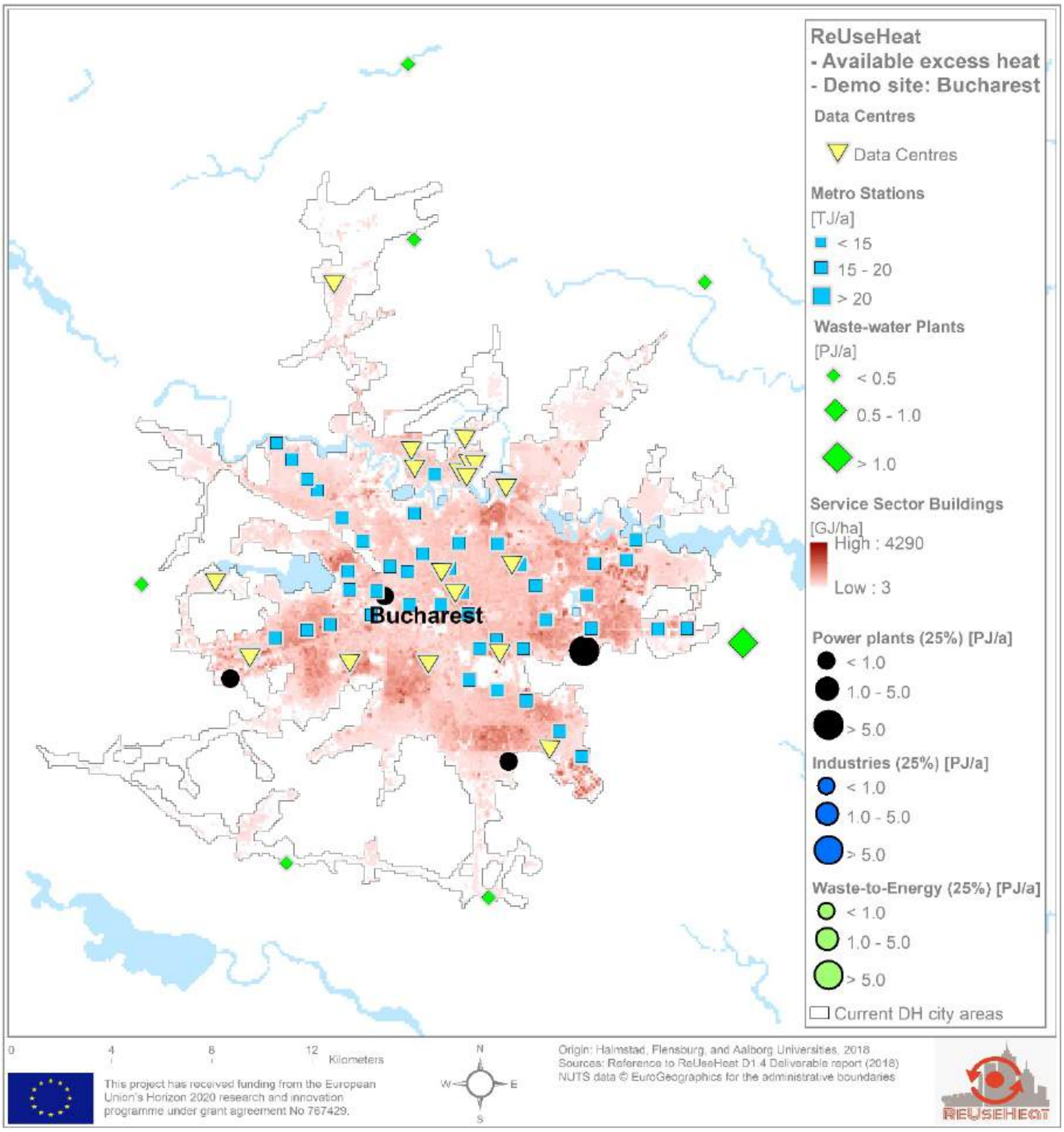

Figure 36. Available excess heat from unconventional and conventional urban excess heat sources in the demo-site of Bucharest (RO).

At the Bucharest demo-site, depicted in Figure 36 and further summarised in Table 47 and Table 48 below, the total sum of available excess heat from all considered sources amounts to 10.8 PJ annually. This heat is available from a total 85 activities: 45 metro stations (0.8 PJ), 24 data centres (1.8 PJ), 12 waste water treatment plants (2.2 PJ) and four conventional sources (2.8 PJ, at 25% of maximal theoretical potential). Available excess heat from service sector buildings is anticipated at 3.2 PJ. The source category to be demonstrated in Bucharest is appropriately a metro station, and, according to the used data, all the four studied unconventional urban excess heat source categories are represented in this city.

10.3 Madrid (Service sector buildings)

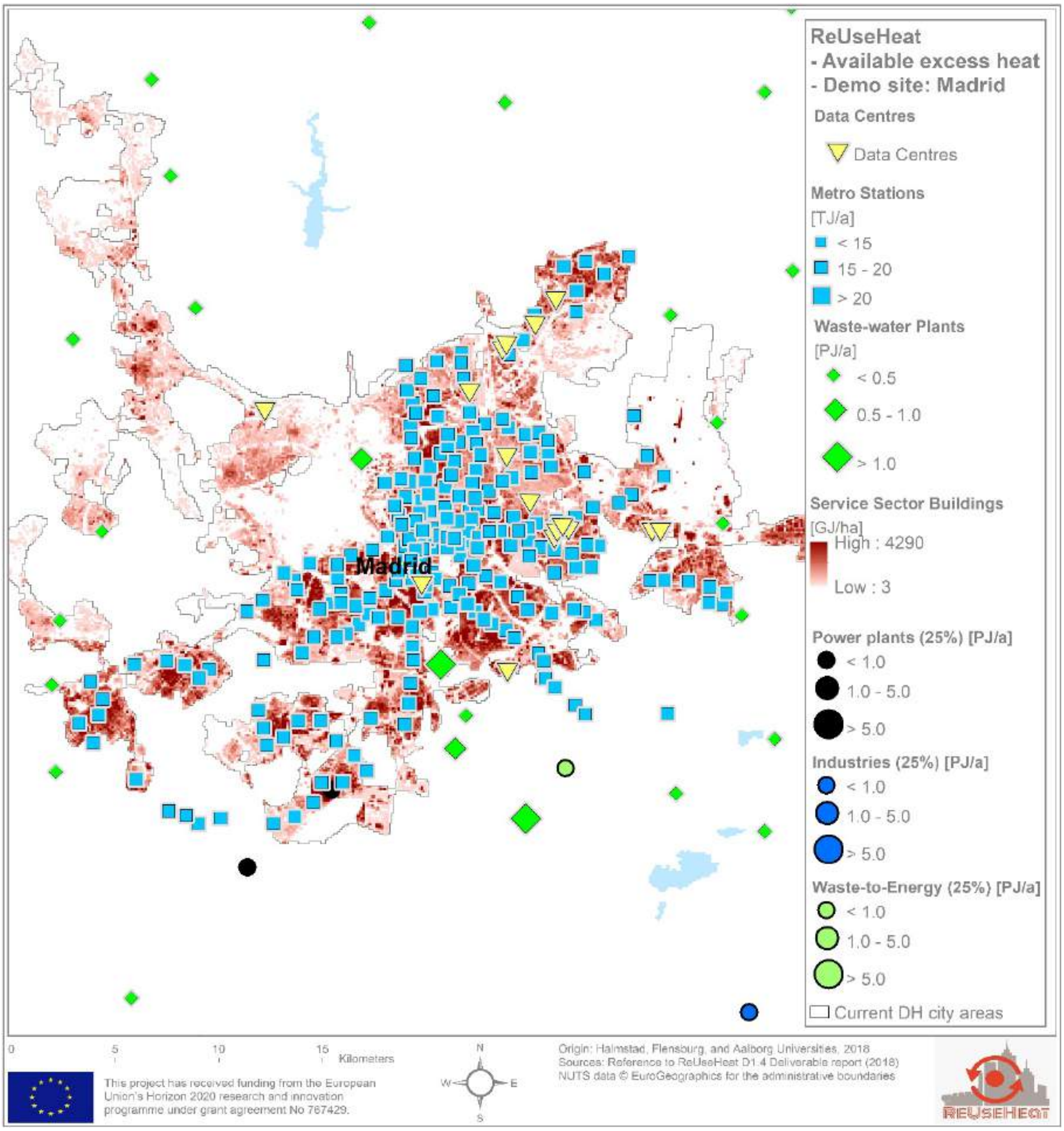

Figure 37. Available excess heat from unconventional and conventional urban excess heat sources in the demo-site of Madrid (ES).

For the Madrid demo-site, depicted in Figure 37 and further summarised in Table 47 and Table 48 below, the total sum of available excess heat from all considered sources amounts to 40.5 PJ annually. This heat is available from a total 318 activities, mainly so from a total of 233 identified underground metro stations (4.0 PJ). Additional contributions come from

19 data centres (6.1 PJ), 59 waste water treatment plants (7.6 PJ) and seven conventional sources (1.4 PJ, at 25% of maximal theoretical potential). Noteworthy, at this south-European location, the available excess heat potential from service sector buildings is found at 21.4 PJ, which may reflect the generally higher cooling demands found at these latitudes. The source category to be demonstrated in Madrid is appropriately service sector buildings, in this particular case a hospital. According to the used data, all the four studied unconventional urban excess heat source categories are represented in this city.

10.4 Nice (Waste water treatment plants)

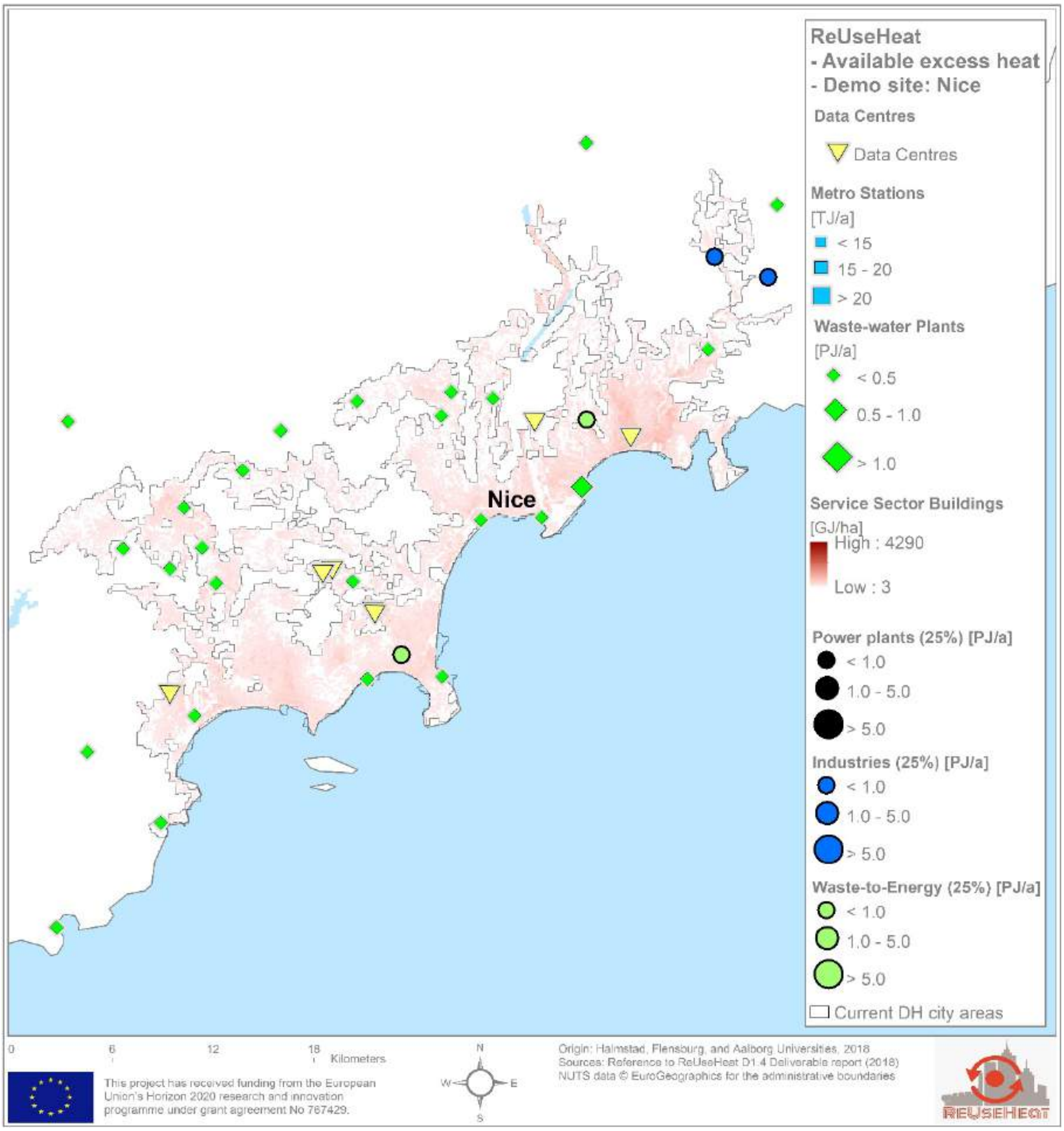

Figure 38. Available excess heat from unconventional and conventional urban excess heat sources in the demo-site of Nice (FR).

At the Nice demo-site, finally, as outlined in Figure 38 and further summarised in Table 47 and Table 48 below, the total sum of available excess heat from all considered sources amounts to 5.9 PJ annually. As can be seen in the map, there is no metro system in the city of Nice, at least not according to the used datasets. However, excess heat is considered available from 37 waste water treatment plants (1.9 PJ), from seven data centres (1.7 PJ), and also from four conventional sources (1.3 PJ, at 25% of maximal theoretical potential). Available excess heat from service sector buildings is assessed at 1.0 PJ annually. The source category to be demonstrated in Nice is accordingly a waste water treatment plant.

10.5 Summary

In summary, the four demo-sites together host a total of 482 urban excess heat activities, if including also 19 conventional sources such as power plants, energy intensive industrial facilities and Waste-to-Energy plants, which may be observed in Table 47. Given that the source category of service sector buildings are modelled in this work in the form a continuous raster representation, for which no floor area summary was made at this stage, the indication given in Table 47 is merely to state that, yes, excess heat from service sector buildings is an option within these citifies.

Table 47. Summary overview of the number of excess heat sources located inside or within 20 kilometres of the four demo-sites (all being urban district hearting areas)

Demo Name	Data Centres [n]	Metro Stations [n]	Service Sector Buildings (Inside)	Waste water treatment plants [n]	Conventional [n]	Total Sources [n]
Brunswick	-	-	Yes	27	4	31
Madrid	19	233	Yes	59	7	318
Nice	7	-	Yes	37	4	48
Bucharest	24	45	Yes	12	4	85
Total	**50**	**278**	**-**	**135**	**19**	**482**

Most activities are found within the source category of metro stations (58%) followed by those belonging to the category urban waste water treatment plants (28%). While data centres represent a smaller fraction (~10%), the 19 identified conventional sources in these four demo-site locations constitute merely 4% of the total activity count. Noteworthy, all considered source categories are present only in the Madrid and the Bucharest case. Neither Brunswick, nor Nice, have metro systems in operation at current, and in Brunswick, the demo object itself will apparently become the first data centre in the city.

If, complementary, considering the annual volumes of available urban excess heat modelled for the four demo-sites, as shown in Table 48, some 71 PJ represents the total sum. The Madrid demo-site, highly impacted by the large anticipated contribution from the service sector potential found here, represents 57% of the total, while Nice represents the smallest fraction at some ~8%.

In terms of sector category volumes, if neglecting the dominating 36% share found for service sector buildings, the contribution from conventional sources (despite here being reduced to a fourth of its full maximal theoretical excess heat potential), is the second largest source at 25%, followed by that of waste water treatment plants at ~18%. Data centres and metro stations account for 14% and 7% respectively.

Table 48. Summary of available excess heat inside or within 20 kilometres of the four demo-sites

Demo Name	Data Centres (65%) [PJ/a]	Metro Stations [PJ/a]	Service Sector Buildings [PJ/a]	Waste water treatment plants [PJ/a]	Conventional (25%) [PJ/a]	Total
Brunswick	-	-	0.1	1.2	12.2	13.6
Madrid	6.1	4.0	21.4	7.6	1.4	40.5
Nice	1.7	-	1.0	1.9	1.3	5.9
Bucharest	1.8	0.8	3.2	2.2	2.8	10.8
Total	**9.6**	**4.8**	**25.7**	**12.9**	**17.8**	**70.8**

11 Main results*

By compilation of the specific source category results for the seven unconventional urban excess heat sources studied, as accounted for in the above, it is now possible to present the main results and findings from this work. In the following, this will be done by first summarising the total count of urban excess heat facilities identified for each category, secondly, to summarise the available excess heat potential found at these locations, and thirdly, to summarise the corresponding accessible excess heat potential assessed for these.

In terms of output data characteristics, as described in Table 49, all results from the modelling of the seven source categories has been assembled in tabular formats, meaning regular matrix assemblies in e.g. MS Excel, MS Access, as well as geospatial databases. The corresponding geometries for the geographical output layers are also specified in this table. Notably, for the two source categories of metro stations and waste water treatment plants, the outputs from this work are part of the PETA 4.3 web map, since mid-November 2018, where they are represented as operational layers.

By the described availability of the output data, a project internal relational database is being developed by which these results will be made available for the energy system modelling assignment in T1.3, as well as for the explicit demo-site modelling in T1.4. Public disseminations of map layers also for other source categories is an alternative which is currently under evaluation. If found relevant, mainly so with respect to data accuracy and representativeness, it is possible that this will be made available at a later stage.

Table 49. Output data characteristics for the modelling and mapping of the seven unconventional urban excess heat sources

Source	**Modelling (format)**	**Mapping (geometry)**	**Description**
Data centres	Tabular	Point sources	Results available both as tables (national level) and map layers (facilities, locations only).
Metro stations	Tabular	Point sources	Results available both as tables and map layers at station level. Represented at PETA 4.3 from November, 2018
Food production facilities	Tabular	Point sources	Results available both as tables and map layers at facility level.
Food retail stores	Tabular	Point sources	Results available both as tables and map layers at store level.
Service sector buildings	Tabular	Raster (100x100m)	Results available both as tables (national) and map layers (by UMZDH areas).
Residential sector buildings	Tabular	Raster (100x100m)	Results available both as tables (national) and map layers (by UMZDH areas).
Waste water treatment plants	Tabular	Point sources	Results available both as tables and map layers at facility level. Represented at PETA 4.3 from November, 2018

For all of the EU28 member states, the total count of unconventional urban excess heat sources that here has been mapped by point source geometries (data centres, metro stations, food production facilities, food retail stores, and waste water treatment plants), is found at 70,771 activities in all, as can be seen in Table 50. Among these, food retail stores are clearly the dominating category (59%) followed by waste water treatment plants (33%), food production facilities (4%) metro stations (3%) and data centres (2%). Three member states stand out with respect to total number of activities, as Germany (25%), France (13%), and the United Kingdom (11%), together represent just about half (49%) of the total population of identified activities.

From Table 50 it is further clear that some member states host only a very limited number of activities, in some instances fewer than 100, which is well below the specific average count of 2528 source category activities per country, corresponding to 3.6% of the total number of considered unconventional urban excess heat sources in this study.

Table 50. Number of unconventional urban excess heat sources in EU28 by the five sources categories represented by point source geometry

CC	Data Centres	Food Production	Food Retail	Metro Stations	Waste water treatment plants	Total	Share
AT	17	19	2076	48	634	**2794**	4%
BE	32	111	1396	47	402	**1988**	3%
BG	20	5	151	29	104	**309**	0%
CY	13	-	26	-	15	**54**	0%
CZ	24	52	627	53	600	**1356**	2%
DE	203	321	12541	318	4244	**17627**	25%
DK	29	31	1450	9	343	**1862**	3%
EE	10	4	148	-	57	**219**	0%
EL	14	6	156	37	159	**372**	1%
ES	59	276	1936	407	2020	**4698**	7%
FI	18	24	776	17	163	**998**	1%
FR	147	493	4539	441	3610	**9230**	13%
HR	5	16	268	-	81	**370**	1%
HU	8	36	1244	44	747	**2079**	3%
IE	22	66	367	-	167	**622**	1%
IT	67	184	1554	214	3953	**5972**	8%
LT	11	9	603	-	75	**698**	1%
LU	15	1	64	-	33	**113**	0%
LV	17	1	190	-	89	**297**	0%
MT	8	-	9	-	4	**21**	0%
NL	97	147	343	25	337	**949**	1%
PL	31	166	3094	27	1665	**4983**	7%
PT	26	42	744	48	467	**1327**	2%
RO	48	27	660	45	556	**1336**	2%
SE	53	39	886	45	432	**1455**	2%
SI	7	8	419	-	91	**525**	1%
SK	14	13	634	-	263	**924**	1%
UK	254	390	4931	140	1878	**7593**	11%
EU28	**1269**	**2487**	**41,832**	**1994**	**23,189**	**70,771**	**100%**
Share	2%	4%	59%	3%	33%	100%	

If limited by the spatial dimension, i.e. if applying the study default restraint of excluding activities not inside or within 2 kilometres from current urban district hearting areas, as presented in Table 51 below, the total number of considered activities is reduced to 27,703 instances (some 39% of the total count). Among these, food retail stores remain the largest share (73%) followed by waste water treatment plants (14%). Metro stations now represent a significantly larger share of the total (7%), which is expected since these mostly are located inside urban areas. By this limitation, 997 data centres constitute 4% of the total count while food production facilities are reduced from 2487 to 669 counts.

In correspondence with the above, a few member states still stand out with respect to total number of activities. At the largest count we again find Germany (21%), which at these conditions clearly surpasses France, Poland, and the United Kingdom, all at 11%. Together these four member states represent more than half (54%) of the total population. The average member state count is here found at 989, which equates to approximately 3.6% of the total. Two countries, Cyprus and Malta, which under unrestrained conditions host 54 and 21 activities respectively, fall completely out of view, since no records of operational district heating systems have been found for the two member states.

Table 51. Number of unconventional urban excess heat sources in EU28 by the five sources 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	16	14	1272	48	231	**1581**	6%
BE	29	68	942	47	218	**1304**	5%
BG	19	-	100	29	13	**161**	1%
CY		-	-	-	-	**0**	0%
CZ	22	31	571	53	369	**1046**	4%
DE	187	77	4712	318	418	**5712**	21%
DK	28	23	1055	9	199	**1314**	5%
EE	10	3	117	-	45	**175**	1%
EL	1	-	-	-	3	**4**	0%
ES	36	21	364	370	57	**848**	3%
FI	17	19	539	17	106	**698**	3%
FR	124	92	1759	419	597	**2991**	11%
HR	4	10	117	-	12	**143**	1%
HU	8	24	791	44	113	**980**	4%
IE	21	5	96	-	6	**128**	0%
IT	39	25	453	185	194	**896**	3%
LT	9	3	403	-	33	**448**	2%
LU	7	-	22	-	5	**34**	0%
LV	17	1	139	-	35	**192**	1%
MT		-	-	-	-	**0**	0%
NL	62	32	75	25	64	**258**	1%
PL	29	91	2468	27	445	**3060**	11%
PT	13	4	90	48	14	**169**	1%
RO	47	13	446	45	76	**627**	2%
SE	45	28	578	45	232	**928**	3%
SI	7	5	261	-	42	**315**	1%
SK	11	12	469	-	153	**645**	2%
UK	189	98	2332	125	302	**3046**	11%
EU28	**997**	**699**	**20,171**	**1854**	**3982**	**27,703**	**100%**
Share	4%	3%	73%	7%	14%	100%	

11.1 Available excess heat*

In terms of the assessed potential for available excess heat, i.e. rejected heat conceived available for recovery at each source category, the modelled total volume amounts to some 1842 PJ annually, as outlined in Table 52. Here, despite not having the highest count of facilities, the relative contribution from waste water treatment plants (41%) constitute the largest contribution, followed by service sector buildings (29%), data centres (12%), and residential sector buildings (12%). Food retail stores, while constituting 59% of the total count, represent only 7% of the available excess heat potential, which is an indication of the relatively lower excess heat volumes per facility in this sector.

At this overview perspective it is quite clear that excess heat recoveries from food production facilities and metro systems, albeit likely feasible solutions in many locations around Europe, remain minor contributors in terms of total excess heat potential volumes, at least by judging from the results generated here. For metro stations, a total annual excess heat volume of 35.3 PJ, which in the context might seem neglectable, still represents a significant amount of energy which may certainly be worth the recovery.

Table 52. Available excess heat in EU28 from the seven sources categories [PJ/a]

CC	DC	FP	FR	MS	RSB	SSB	WWTP	Total	Share
AT	5.1	0.079	5.5	0.8	3.22	2.6	20.7	**37.9**	2%
BE	6.7	0.770	3.8	0.8	0.85	7.4	11.6	**32.0**	2%
BG	2.4	0.003	0.5	0.5	3.72	5.7	7.7	**20.6**	1%
CY	0.4	-	0.1	-	0.18	4.1	1.1	**5.8**	0%
CZ	4.6	0.019	2.0	0.8	0.34	1.5	14.1	**23.4**	1%
DE	42.4	1.674	38.9	4.8	2.54	38.7	165.8	**294.9**	16%
DK	2.6	0.502	4.0	0.1	0.45	1.7	11.2	**20.6**	1%
EE	0.6	0.024	0.3	-	0.28	1.4	2.3	**4.9**	0%
EL	4.4	0.002	0.6	0.8	15.87	79.0	11.2	**111.8**	6%
ES	19.0	0.615	7.6	7.8	36.32	116.8	64.2	**252.3**	14%
FI	6.6	0.285	1.9	0.2	0.10	1.9	12.0	**23.0**	1%
FR	36.2	1.804	14.8	7.9	7.09	51.0	90.5	**209.3**	11%
HR	1.3	0.023	1.0	-	0.02	2.4	4.0	**8.7**	0%
HU	3.0	0.114	3.8	0.8	0.99	3.3	13.5	**25.4**	1%
IE	2.1	1.021	1.1	-	0.02	0.5	6.6	**11.4**	1%
IT	23.4	0.290	5.0	4.5	62.55	146.4	81.0	**323.2**	18%
LT	0.8	0.067	1.7	-	0.17	0.4	4.4	**7.6**	0%
LU	0.5	0.010	0.2	-	0.02	0.2	1.0	**1.9**	0%
LV	0.5	0.003	0.5	-	0.01	0.2	2.2	**3.4**	0%
MT	0.2	-	0.0	-	0.00	2.9	0.4	**3.6**	0%
NL	8.7	1.194	1.0	0.4	0.09	4.7	26.8	**42.8**	2%
PL	10.9	0.561	8.2	0.4	1.96	7.7	54.5	**84.2**	5%
PT	3.8	0.065	2.8	1.1	0.15	9.3	11.0	**28.3**	2%
RO	3.5	0.057	2.4	0.8	2.72	6.9	17.5	**33.9**	2%
SE	10.4	0.174	2.2	0.6	1.67	5.0	16.5	**36.6**	2%
SI	1.1	0.007	1.2	-	0.01	2.1	2.2	**6.6**	0%
SK	2.0	0.013	1.7	-	0.01	0.6	5.5	**9.9**	1%
UK	24.9	2.559	13.0	2.2	0.75	31.8	103.3	**178.5**	10%
EU28	**228.0**	**11.9**	**125.7**	**35.3**	**142.1**	**536.2**	**763.0**	**1842.3**	**100%**
Share	12%	1%	7%	2%	8%	29%	41%	100%	

If again applying the default spatial restraint (inside or within 2 kilometres of current urban district heating areas), the available excess heat potential is reduced to 960 PJ per year, which can be seen in Table 53. The reduced volume represents approximately 52% of the given total, thus principally half of this. In the conclusions of this work, see section 13 below, this volume (960 PJ) is consequently stated as the found annually available excess heat potential for the EU28 under current conditions.

For available excess heat at this spatial setting, waste water treatment plants (43%) remains the main contributing source, followed again by service sector buildings (20%), data centres (19%), and residential sector buildings (8%). Highest potential volumes are found in Germany (17%, at some 160 PJ), France (15%, 142 PJ), and Italy (13%, 121 PJ). In comparison to a conceivable EU28 member state specific average value for all source categories of 66 PJ per year and country, the corresponding average under the given spatial restraint is found at 34 PJ per year and country. Hereby it may be concluded that 22 of the 28 member states host available excess heat potentials below the country specific average value derivable at these conditions, and only six are found above this reference level.

*Table 53. Available excess heat in EU28 from the seven sources categories [PJ/a], inside or within 2 kilometres of urban district heating areas. Note: * available excess heat is the same value as accessible excess heat*

CC	DC	FP	FR*	MS	RSB	SSB	WWTP	Total	Share
AT	4.8	0.054	3.5	0.8	3.22	1.9	15.9	**30.1**	3%
BE	6.1	0.434	2.6	0.8	0.83	5.5	9.5	**25.8**	3%
BG	2.2	-	0.4	0.5	3.30	3.9	4.0	**14.3**	1%
CY	0.0	-	-	-	0.00	0.0	-	**0.0**	0%
CZ	4.2	0.013	1.9	0.8	0.33	1.2	13.2	**21.5**	2%
DE	39.0	0.332	14.5	4.8	2.51	17.7	80.8	**159.7**	17%
DK	2.5	0.354	3.0	0.1	0.44	1.3	9.7	**17.3**	2%
EE	0.6	0.018	0.3	-	0.28	1.0	2.3	**4.4**	0%
EL	0.3	-	-	-	0.00	0.0	0.2	**0.5**	0%
ES	11.6	0.053	1.4	7.0	17.56	39.6	15.0	**92.2**	10%
FI	6.3	0.232	1.3	0.2	0.10	1.4	8.1	**17.7**	2%
FR	30.6	0.343	5.7	7.4	7.06	33.4	57.0	**141.6**	15%
HR	1.0	0.015	0.4	-	0.02	1.7	2.7	**5.8**	1%
HU	3.0	0.104	2.6	0.8	0.98	2.7	10.7	**20.9**	2%
IE	2.0	0.030	0.3	-	0.01	0.3	4.0	**6.6**	1%
IT	13.6	0.039	1.5	3.8	29.45	45.9	26.6	**121.0**	13%
LT	0.7	0.022	1.2	-	0.17	0.3	3.4	**5.7**	1%
LU	0.2	-	0.1	-	0.01	0.1	0.3	**0.7**	0%
LV	0.5	0.003	0.4	-	0.01	0.2	2.0	**3.1**	0%
MT	0.0	-	-	-	0.00	0.0	-	**0.0**	0%
NL	5.5	0.168	0.2	0.4	0.09	1.6	10.2	**18.2**	2%
PL	10.2	0.313	6.7	0.4	1.89	5.3	44.5	**69.3**	7%
PT	1.9	0.002	0.3	1.1	0.14	3.2	2.5	**9.2**	1%
RO	3.5	0.024	1.6	0.8	2.60	5.2	12.1	**25.8**	3%
SE	8.9	0.119	1.5	0.6	1.58	3.6	13.5	**29.8**	3%
SI	1.1	0.006	0.8	-	0.01	1.1	1.3	**4.2**	0%
SK	1.6	0.012	1.4	-	0.01	0.5	5.0	**8.5**	1%
UK	18.5	0.494	6.0	2.0	0.52	16.1	62.1	**105.6**	11%
EU28	**180.4**	**3.2**	**59.7**	**32.4**	**73.1**	**194.3**	**416.6**	**959.7**	**100%**
Share	19%	0%	6%	3%	8%	20%	43%	100%	

11.2 Accessible excess heat*

To arrive finally at the practical utilisation potential of the annual available excess heat volumes assessed for the considered source categories, i.e. the accessible excess heat potential, a summary is presented in Table 54. In this summary, which reflects the total accessible excess heat potential under the default spatial restraint, i.e. inside or within 2 kilometres of current urban district heating areas, and further by uniform application of a practical COP of 3.0, the EU28 final volume amounts to 1410 PJ per year. In the conclusions of this work, accordingly, this volume (1410 PJ) is hence stated as the found annual accessible excess heat potential for the EU28 under current conditions.

*Table 54. Accessible excess heat in EU28 from the seven sources categories [PJ/a], inside or within 2 kilometres of urban district heating areas at a practical COP of 3.0. Note: * accessible excess heat is the same value as available excess heat*

CC	DC	FP	FR*	MS	RSB	SSB	WWTP	Total	Share
AT	7.2	0.081	3.5	1.2	4.84	2.8	23.9	**43.4**	3%
BE	9.1	0.651	2.6	1.2	1.24	8.3	14.3	**37.4**	3%
BG	3.4	0.000	0.4	0.7	4.95	5.9	6.0	**21.2**	2%
CY	0.0	0.000	-	-	0.00	0.0	-	**0.0**	0%
CZ	6.3	0.019	1.9	1.1	0.49	1.7	19.8	**31.4**	2%
DE	58.6	0.498	14.5	7.2	3.76	26.5	121.2	**232.3**	16%
DK	3.7	0.531	3.0	0.2	0.67	1.9	14.5	**24.5**	2%
EE	0.9	0.026	0.3	-	0.42	1.5	3.4	**6.5**	0%
EL	0.5	0.000	-	-	0.00	0.0	0.3	**0.7**	0%
ES	17.4	0.079	1.4	10.5	26.35	59.4	22.5	**137.6**	10%
FI	9.4	0.348	1.3	0.3	0.15	2.2	12.1	**25.9**	2%
FR	45.8	0.515	5.7	11.1	10.60	50.2	85.5	**209.5**	15%
HR	1.5	0.023	0.4	-	0.02	2.6	4.0	**8.6**	1%
HU	4.6	0.156	2.6	1.2	1.46	4.1	16.1	**30.1**	2%
IE	3.0	0.044	0.3	-	0.01	0.4	6.0	**9.7**	1%
IT	20.5	0.058	1.5	5.8	44.18	68.9	39.8	**180.7**	13%
LT	1.0	0.033	1.2	-	0.25	0.4	5.1	**7.9**	1%
LU	0.4	0.000	0.1	-	0.02	0.1	0.5	**1.0**	0%
LV	0.8	0.005	0.4	-	0.01	0.3	3.0	**4.5**	0%
MT	0.0	0.000	-	-	0.00	0.0	-	**0.0**	0%
NL	8.3	0.252	0.2	0.6	0.13	2.4	15.3	**27.2**	2%
PL	15.3	0.470	6.7	0.6	2.84	7.9	66.8	**100.6**	7%
PT	2.8	0.003	0.3	1.7	0.21	4.8	3.8	**13.7**	1%
RO	5.2	0.036	1.6	1.2	3.90	7.8	18.2	**37.9**	3%
SE	13.3	0.179	1.5	0.9	2.36	5.4	20.3	**44.0**	3%
SI	1.6	0.008	0.8	-	0.02	1.6	1.9	**5.9**	0%
SK	2.4	0.018	1.4	-	0.01	0.7	7.5	**12.0**	1%
UK	27.8	0.741	6.0	2.9	0.78	24.1	93.2	**155.5**	11%
EU28	**270.6**	**4.8**	**59.7**	**48.6**	**109.7**	**291.5**	**624.9**	**1409.7**	**100%**
Share	19%	0%	4%	3%	8%	21%	44%	100%	

By the uniform application of the COP value, the relative shares by which the six concerned source categories are represented in this total sum remains identical to that found for the corresponding available excess heat potential under the given spatial settings. For the seventh source category in this respect, the food retail sector, heat pumps were excluded from the modelling, as explained previously, why the values given for accessible excess heat equals those stated for available excess heat.

In Table 54, it may be observed that some 232 PJ of annual energy, corresponding to some 65 TWh, may be utilised in Germany alone (representing the largest study volume for a single country), closely followed by France at 210 PJ (58 TWh), Italy at 181 PJ (50 TWh), and the United Kingdom at 156 PJ (43 TWh). In terms of a country specific average value, an approximate value of 50 PJ per year, thus corresponding to some 14 TWh annually, is conceivable based on the given output data.

If seen from the perspective of source categories, the accessible annual excess heat potential from waste water treatment plants is thus found at roughly 625 PJ (174 TWh), that of service sector buildings at 292 PJ (81 TWh), that of data centres at 271 PJ (75 TWh), and that of residential sector buildings at 110 PJ (30 TWh). The annual accessible excess heat potential from metro stations amounts to 49 PJ (14 TWh), while that of the food production sector – which here has been represented by large-scale facilities only – is found at some 5 PJ per year (1.3 TWh).

For reference, the four strata of resulting outputs from the modelling reported here, i.e. available and accessible excess heat, without and with the default spatial restraint, is displayed in Figure 39. In this staple bar graph are also included the originally conceived recovery potential volumes stated in the project proposal (in black). From this figure, the significance of the distinction between, first of all available vs. accessible excess heat, secondly with regards to the spatial dimension, consistently maintained throughout this work, becomes strikingly apparent.

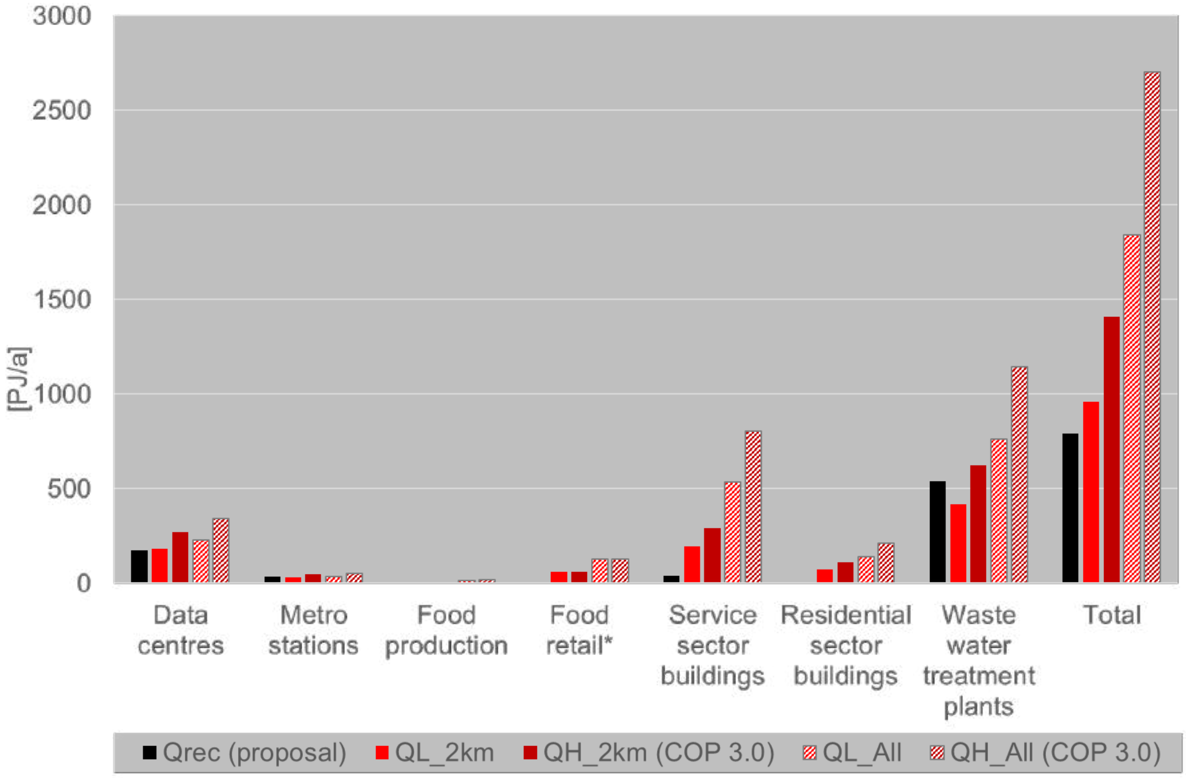

Figure 39. Summary overview of modelled available and accessible excess heat total volumes inside or within 2 kilometres of urban district heating areas (2km) vs. volumes unrestricted by local conditions (all), by source category and with comparison to recoverable excess heat volumes (Q_{rec}), as anticipated in the project proposal.

For the former, especially when considering the far-right bars signifying total volumes, the marked differences in magnitudes between available and accessible potentials signals the necessity to incorporate such concepts in low-temperature excess heat source potential assessments like the one performed here. By this reasoning, it is appropriate to speak about recovery potentials, in general, only when these have first been properly defined.

As for the latter, the spatial dimension, which here is applied in the fundamental recognition of the fact that, if no means are in place by which to actually recover available excess heat, then these resources are principally only imaginary. Thus, although improvable, as also discussed in section 12 below, the key method approach of delimiting total potentials by a set of default spatial restraints, allows for an appreciation of feasibly recoverable volumes. As can be seen, the assessed total potential for available excess heat inside or within 2 kilometres of current urban district heating areas ("QL_2km"), approximates the stipulated 789 PJ potential quite well ("Qrec (proposal)").

12 Discussion*

Recovery and large-scale utilisation of excess heat from unconventional as well as from conventional sources represents a structural energy efficiency measure by which total primary energy demands for low-temperature purposes may realistically be reduced by means of fuel substitution. Perhaps most pronounced among such low-temperature energy demands are those concerning space heating and domestic hot water preparation in residential and service sector buildings, final demands which in EU28 today amount to approximately 10-11 EJ per year.

A fundamental prerequisite for the feasibility of such large-scale recoveries is however that appropriate infrastructures by which to transport and distribute this heat is in place. In this particular sense, current and future deployment levels of district heating systems have a decisive impact on the degree by which the vast volumes of excess heat currently present in the European Union may become recycled and used in the coming years. Prospects for excess heat recoveries are therefore, in general, less likely determined by for example city sizes, temperature levels, and energy prices etc., as they are by the sheer presence, or not, of such large-scale heat distribution infrastructures.

As for the potentials assessed in this work, albeit subjected to a spatial dimension restraint intended to capture and intercept this important aspect, the level of detail by which this has been performed here is improvable. By combining the urban morphological zones (UMZ) dataset with the Halmstad University (HU) database on European district heating systems, a viable proxy for current urban district heating areas has been obtained. However, whereas the UMZ dataset describes urban areas in general (and not the physical outstretch of district heating networks in particular), and as the HU database only covers an anticipated 70% of the current stock of EU28 district heating systems, this certainly leaves room for ameliorations.

In general, and by our own evaluation, the level of accuracy attained in modelling and mapping the excess heat potentials for the seven considered source categories, classified here by three levels (low, medium, and high), is presented in Table 55. For the first and third categories, data centres and food production facilities, the low modelling accuracy designated in these cases are due mainly to the scarcity of quantitative data at facility level, which led to the development of alternative approaches. In terms of mapping, the accuracy is considered high for the both modelled instances, however, since the actual number of European activities within these two categories currently in operation may not fully be represented by the used dataset, the overall evaluation has been set at medium.

Table 55. Level of accuracy (low, medium, and high) in modelling and mapping the seven unconventional urban excess heat sources

Source	Modelling	Mapping
Data centres	Low	Medium
Metro stations	Medium	High
Food production facilities	Low	Medium
Food retail stores	Medium	High
Service sector buildings	High	Medium
Residential sector buildings	High	High
Waste water treatment plants	High	High

The medium accuracy level designated for the modelling of metro stations is due solely to the fact that potentials had to be assessed at average city level, and not by unique station levels, this since no open dataset could be found by which station specific traffic intensities could be established. This aspect may be improved in future studies if suitable input data, such as for example person entrees and exits (which indeed was located for one study city: the city of London), should become available in a higher degree. The accuracy level of the mapping itself, which was performed by laborious georeferencing of some 3300 EU28 heavy rail stations, however, is considered (very) high.

The medium accuracy level designated for the modelling of food retail stores is due to the necessity to develop and use several simplifications and generalisations as regards the input data and modelling parameters. This is also recognised in the comment section associated to this source category. However, in order at all to produce an EU28 scope model, the use of such simplifications is in principle unavoidable, whereas for more narrow study objects, say a few regions or one country, less generalised approaches should be more apt.

As for both residential and service sector buildings, the accuracy level of modelling has been found high in both instances, although rejected heat from both sectors were conceived principally as being performed by means of central cooling devices only. In reality, there are several other technologies by which cold may be provided to such buildings, for example individual cooling devices, however, these, as well as other possible technologies, were exempted from this modelling since the focus here has been large-scale recovery by means of heat distribution infrastructures. In terms of mapping, the level of accuracy was considered medium for service sector buildings, due to a geographical generalisation made regarding the spatial distribution of shares of cooled floor areas, but high for the residential sector, where instead an extract of high-density building areas only constituted the study population. Other than this, the mapping of both residential and service sector buildings was performed at a very high level of accuracy (hectare grid resolution), an accuracy level designated also to the point source charting of some 23,200 EU28 urban waste water treatment plants.

All the resulting outputs from the work performed in this study is further being compiled in a coherent relational database for the purpose of internal project dissemination. The main motivation for this is the provision of input data for additional work being done in the project. This T1.2 result dataset will be of use mainly so with reference to the national level energy system modelling being performed for the four demo-site member states in T1.3, as well as for the dedicated demo-site modelling being performed in T1.4.

13 Conclusions*

To conclude, this report has presented the original and the revised work performed in Task T1.2 of the ReUseHeat project, which objective has been to assess the accessible EU28 urban excess heat recovery potential from seven unconventional urban excess heat sources. These seven source categories are, in alphabetic order, data centres, food production facilities, food retail stores, metro stations, residential sector buildings, service sector buildings, and waste water treatment plants. The report has presented in overview, as well as in detail, the concepts, data, basic premises, and methods, used to produce the final resulting outputs.

In terms of the seven studied urban excess heat source categories, a total of 70,771 unique activities constitute the total population of study objects, not including residential and service sector buildings which were modelled not as point sources but in the form of continuous raster representations. Among these, a total of 41,832 food retail stores and some 23,200 urban waste water treatment plants constitute the largest number of facilities, followed by some 2500 food production facilities, just about 2000 underground metro stations, and some 1300 data centres. To obtain this information, various data repositories and publicly available data sources has been utilised, as well as other sources, such as academic literature, text books, and personal contacts, in order to develop appropriate conceptual approaches by which to assess the given potentials.

The report has further introduced two new and vital concepts by which recovery of low-temperature excess heat, e.g. heat below 50°C, may be distinguished. The first of these concepts refer to the heat inherent at a given source, meaning the heat that is possible to recover from a source itself, which has been labelled *available* excess heat in this context. The second concept, *accessible* excess heat refers, in the first instance, to rejected heat from condensers in large-scale compressor heat pumps, which for six out of the seven source categories have been the model application by which to make such low-temperature excess heat resources usable in 3rd generation district heating systems. In the second instance, the concept refers to the spatial coherence by which unique source category locations coincide with those of such large-scale heat distribution infrastructures.

In accordance with these two concepts, the main results from this work are those found under a default spatial restraint requiring of a plausible excess heat recovery activity to be located inside or within 2 kilometres of current urban district heating areas in order to be included in the final potential assessments. Complementary to these main results, albeit not consistently accounted for in this report, corresponding excess heat potentials were assessed also for three other spatial restraint settings, namely for those outside or within 10 kilometres, 5 kilometres, or completely within such urban areas. Among these complementary potential assessments were also that of completely unrestricted spatial coherency, meaning the inclusion of all modelled activities in all considered source categories.

As an initial reference for the urban excess heat potentials that were to be assessed in T1.2, upon start-up, a preliminary EU28 recovery potential at 789 PJ per year, stipulated in the original project proposal, has served as a benchmark throughout the working process (starting in October 2017 to November 2018 as regards the original work, and from January to May 2020 for the revision work), as presented in Table 56.

When compared to the final results for available excess heat, thus inside or within 2 kilometres of current urban district heating areas, the assessed potential at 960 PJ per year comes very close to matching the proposed potential. At this setting, the total count of unconventional urban excess heat sources amount to 27,703 unique facilities and plants, of which approximately two thirds are food retail stores (~20,200) and one out of six are waste water treatment plants (3982).

Table 56. Comparison of recoverable excess heat volumes (Q_{rec}), as anticipated in the project grant agreement (p. 31, Part B), and modelled volumes of available excess heat inside or within 2 kilometres of urban district heating areas (2km). [PJ/a]

Source	Qrec (proposal)	QL_2km	Ratio [%]
Data centres	173	180	4%
Metro stations	36	32	-11%
Food production facilities	-	3	-
Food retail stores	-	60	-
Service sector buildings	40	194	485%
Residential sector buildings	-	73	-
Waste water treatment plants	540	417	-23%
Total	**789**	**960**	**22%**

The only main deviance observable in this comparison, given the input information, is that regarding service sector buildings. This is easily explained, however, since the proposed potential refers to hospitals only (in accordance with the dedicated study object in one of four project demonstration sites), while the modelled potential refers to the complete service sector as such.

At the given settings, as presented in Table 56, the corresponding accessible urban excess heat potential for EU28 has been assessed in this work to 1410 PJ annually. This number is thus the final answer to the formal assignment stipulated in the T1.2 task description title, i.e. the “quantification of accessible urban waste heat” for the EU28 countries.

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15 Appendix*

15.1 T1.2 work description

WP1 - Urban waste heat potential identification

Task 1.2: Quantification of accessible urban waste heat.

"The main objective of this task is the identification of urban waste heat potential at the urban level for the EU28 countries both from conventional excess heat sources (e.g. cogeneration facilities, waste-to-energy plants and industrial processes), and unconventional excess heat sources (e.g. metros, urban waste water systems, data centres, and heat from cooling of buildings and refrigeration processes in food production and retail). The conventional heat sources are readily available from previous EU projects Stratego and HRE4. The unconventional excess heat sources reflect the heat sources of the demo (in WP3). To this end, the first step is to perform an analysis to identify the data sources that may contain valuable information for the characterisation of the urban heat sources considered in the project, as well as for the definition of urban areas. Secondly, an analysis of heat supply from the point of view of temperatures and temporality will be carried out.

This is achieved by means of classification and characterisation of typical processes and technologies which represent the considered urban waste heat sources. For this purpose, information will be collected at the NACE code level to identify the urban waste heat sources and a listing based on the NACE classification will serve as a means to associate temperature and temporality to each identified source. This task will build upon work already performed in projects like Heat Roadmap Europe 4, where a first NACE code classification of heat sources was made. This work will be continued and developed for urban waste heat sources in this proposal. Data will be managed and structured for analysis in relational database formats. For the geographical identification and distribution of the considered activities, as well as for advanced spatial data analyses and dissemination options of project findings (for example maps), the project will use Geographical Information Systems (GIS) tools in combination with energy system modelling tools (Task 1.3). This combined approach has been used in other EU projects and is currently being deployed in Heat Roadmap Europe 4. The use of GIS in this project is partly novel since the focus is at the metropolitan level (rather than at the regional or national level) and also since the range of selected excess heat sources extends beyond the scope of previous studies.

The deliverable of task 1.2 is data on available volumes of urban waste heat specified at the NACE class code level for the considered urban waste heat sources. The data will be entered into the database established in Task 1.1, and a summary report will be made on the potential volumes of urban waste heat and of the heat sources at the EU28 level, the national level and the urban level. Information on conventional heat sources such as cogeneration, waste-to-energy and industrial processes will be identified for the urban areas that are being studied in the proposal. In this way, knowledge that has been generated in earlier EU projects provides a possibility to understand the total urban waste heat potential including conventional and unconventional heat sources. The report will be used when defining the replicability and scalability strategies which will be reflected in the Handbook".

15.2 Data centres: Q_H at COP 2.5 and COP 3.5

Table 57. Number of EU28 data centres and accessible excess heat inside or within 2 kilometres of urban district heating areas at practical COP of 2.5 and 3.5

MS	Data centres (2km) [n]	QH COP 2.5 (2km) [PJ]	QH COP 3.5 (2km) [PJ]
AT	16	7.9	6.7
BE	29	10.1	8.5
BG	19	3.7	3.1
CY	0	0.0	0.0
CZ	22	7.0	5.9
DE	187	65.1	54.6
DK	28	4.1	3.4
EE	10	1.0	0.8
EL	1	0.5	0.4
ES	36	19.4	16.3
FI	17	10.4	8.8
FR	124	50.9	42.8
HR	4	1.7	1.4
HU	8	5.1	4.3
IE	21	3.3	2.8
IT	39	22.7	19.1
LT	9	1.1	0.9
LU	7	0.4	0.3
LV	17	0.9	0.7
MT	0	0.0	0.0
NL	62	9.2	7.7
PL	29	17.0	14.2
PT	13	3.2	2.7
RO	47	5.8	4.9
SE	45	14.8	12.4
SI	7	1.8	1.5
SK	11	2.7	2.3
UK	189	30.9	25.9
EU28	**997**	**300.6**	**252.5**

15.3 Metro stations: Input model parameters

Table 58. Annual average input parameters for temperature [°C] and relative humidity [%], corresponding to ambient climate condition.

City	Jan		Feb		Mar		Apr		May		Jun		Jul		Aug		Sep		Oct		Nov		Dec	
	°C	%	°C	%	°C	%	°C	%	°C	%	°C	%	°C	%	°C	%	°C	%	°C	%	°C	%	°C	%
Amsterdam	1.5	86	2.0	83	5.5	76	8.5	70	13.0	67	16.0	67	17.5	72	17.5	74	14.5	77	10.5	81	6.0	87	3.0	88
Athens	9.3	72	9.8	71	11.7	68	15.5	62	20.2	58	24.6	52	27.0	48	26.6	49	23.3	56	18.3	66	14.4	73	11.1	73
Barcelona	8.8	69	9.5	66	11.1	73	12.9	69	15.9	68	19.7	67	22.9	67	23.0	72	21.0	74	17.1	74	12.5	72	9.7	70
Berlin	-0.4	88	0.6	85	4.0	78	8.4	73	13.5	71	16.7	72	17.9	76	17.2	78	13.5	81	9.3	86	4.6	90	1.2	91
Bilbao	9.0	72	9.8	70	10.8	70	11.9	71	15.1	71	17.6	72	20.0	73	20.3	74	18.8	73	15.8	73	12.0	74	10.0	73
Brescia	2.0	79	3.0	72	8.0	64	13.0	58	17.0	57	21.0	54	23.0	53	23.0	55	19.0	61	13.0	72	7.0	78	3.0	82
Brussels	2.5	88	3.0	86	6.0	80	8.5	78	13.5	77	15.5	78	17.5	80	23.0	82	15.0	84	10.0	88	5.0	90	3.5	90
Bucharest	-2.4	86	-0.1	82	4.8	71	11.3	63	16.7	62	20.2	61	22.0	58	21.2	57	16.9	61	10.8	73	5.2	84	0.2	87
Budapest	-0.5	79	2.0	74	6.4	66	11.8	59	16.6	61	19.7	61	21.5	59	20.9	61	16.9	67	11.5	72	5.7	78	1.5	80
Catania	10.6	73	10.9	71	12.2	70	14.3	70	17.9	68	22.0	65	25.1	64	25.6	67	23.1	68	19.2	72	15.0	75	11.8	76
Copenhagen	0.0	87	0.0	85	2.0	83	7.0	76	12.0	68	16.0	68	18.0	71	17.0	74	14.0	78	9.0	83	5.0	87	3.0	88
Genoa	8.0	61	8.8	63	11.1	61	13.7	70	17.3	71	20.7	71	23.9	67	23.9	66	21.0	66	17.2	66	12.2	64	9.1	64
Glasgow	3.0	86	4.0	82	5.5	80	8.0	76	10.5	74	13.5	76	15.0	78	15.0	80	12.5	82	9.5	84	6.0	86	4.5	88
Hamburg	-0.5	87	0.0	85	4.0	77	8.0	73	12.5	71	16.5	73	18.0	76	18.0	80	14.5	81	10.0	85	4.5	89	1.5	91
Helsinki	-6.0	89	-6.5	88	-3.5	78	2.5	75	9.0	64	14.0	64	17.5	70	16.0	77	11.5	85	5.5	89	1.0	89	-3.0	91
Lille	2.5	87	3.0	85	6.0	81	9.5	76	12.5	76	15.5	78	17.0	78	17.0	79	15.5	79	10.5	84	6.0	84	3.5	90
Lisbon	11.4	80	12.3	78	13.7	71	15.1	69	17.4	66	20.2	66	22.4	63	22.8	61	21.7	67	18.5	72	14.5	77	11.8	79
London	4.0	88	4.5	84	6.5	79	9.0	73	12.5	72	15.5	70	17.5	72	17.0	75	15.0	80	11.0	85	7.5	88	5.0	89
Lyon	2.0	87	3.5	82	8.0	74	11.0	69	14.5	69	18.5	68	21.0	64	20.0	67	17.5	76	11.5	83	7.0	86	3.0	87
Madrid	5.5	77	7.0	69	9.3	65	11.6	58	15.5	57	20.4	51	24.3	42	23.8	44	20.3	56	14.5	68	8.9	75	5.9	79
Marseille	6.0	78	7.0	73	10.0	71	13.0	67	16.5	68	20.5	65	23.0	61	22.5	64	20.0	71	15.0	76	10.5	79	7.0	79
Milan	1.4	86	4.2	78	8.3	71	12.3	75	16.6	72	20.6	71	23.1	71	22.2	72	18.9	74	13.1	81	6.9	85	2.3	86
Munich	-2.2	83	-0.4	83	3.4	77	7.6	72	12.2	73	15.4	75	17.3	73	16.6	75	13.4	78	8.2	82	2.8	86	-0.9	86
Naples	8.2	75	8.8	73	10.6	71	13.3	70	17.4	70	20.9	71	23.7	70	23.7	69	20.8	73	16.7	74	12.4	76	9.4	75
Newcastle	5.0	79	5.5	76	7.0	73	8.0	73	11.0	71	13.5	72	16.0	73	16.5	73	13.5	76	10.0	77	7.5	81	4.0	80
Nuremburg	-1.0	84	0.0	81	4.0	75	8.0	71	12.5	68	16.5	70	18.0	71	17.5	74	14.5	78	9.0	82	4.0	86	0.0	88
Paris	3.5	89	4.0	84	8.0	75	11.0	69	15.0	69	18.0	69	20.0	70	19.0	72	16.5	78	12.0	84	7.5	89	4.5	89
Prague	-2.0	85	-0.6	82	3.1	76	7.6	70	12.5	70	15.6	71	17.1	70	16.6	72	13.2	77	8.3	81	3.0	85	-0.2	85
Rennes	5.9	87	6.1	83	8.6	79	10.6	75	14.1	76	17.1	76	19.2	76	19.0	78	16.5	82	13.1	86	8.8	88	6.2	89
Rome	7.0	79	8.4	75	10.3	72	13.2	72	17.3	72	21.0	70	24.0	68	23.9	69	21.0	71	16.5	75	11.4	79	7.9	80
Rotterdam	3.0	88	3.0	85	6.0	83	8.0	78	12.0	77	15.0	79	17.0	79	17.0	80	14.0	84	11.0	86	6.0	89	5.0	89
Sofia	-1.5	77	0.7	74	4.8	69	10.4	63	14.6	67	18.0	67	19.8	63	20.7	62	16.1	65	10.7	70	5.1	77	0.6	79
Stockholm	-2.8	85	-3.0	81	0.1	78	4.6	72	10.7	65	15.6	66	17.2	72	16.2	75	11.9	81	7.5	84	2.6	88	-1.0	87
Toulouse	5.0	80	5.5	70	9.0	64	11.5	61	14.5	62	18.5	59	21.0	57	21.0	56	18.5	62	13.0	68	9.0	77	5.5	82
Turin	2.0	83	4.0	68	9.0	62	13.0	57	18.0	66	21.0	54	24.0	50	23.0	54	19.0	60	13.0	73	7.0	78	3.0	80
Warsaw	-3.3	86	-2.1	85	1.9	77	7.7	73	13.5	68	16.7	69	18.0	74	17.3	74	13.1	77	8.2	82	3.2	86	-0.9	88
Vienna	-1.5	79	0.0	76	4.5	69	10.5	64	14.5	66	18.5	66	20.0	64	19.5	68	15.5	74	10.5	78	5.0	80	1.0	80

15.4 Metro stations: Modified output model parameters

Table 59. Modified average output parameters for temperature [°C] and relative humidity [%], corresponding to station climate condition.

City	Jan		Feb		Mar		Apr		May		Jun		Jul		Aug		Sep		Oct		Nov		Dec	
	°C	%	°C	%	°C	%	°C	%	°C	%	°C	%	°C	%	°C	%	°C	%	°C	%	°C	%	°C	%
Amsterdam	15.0	34	15.0	34	15.0	40	15.0	46	15.0	59	25.5	37	27.0	40	27.0	41	15.0	75	15.0	60	15.0	48	15.0	39
Athens	15.0	49	15.0	50	15.0	55	25.0	34	29.7	33	30.0	38	30.0	40	30.0	40	30.0	38	27.8	37	15.0	70	15.0	57
Barcelona	15.0	46	15.0	46	15.0	57	15.0	60	25.4	38	29.2	38	30.0	44	30.0	48	30.0	43	26.6	41	15.0	61	15.0	49
Berlin	15.0	31	15.0	32	15.0	37	15.0	47	15.0	64	26.2	40	27.4	43	26.7	44	15.0	74	15.0	59	15.0	45	15.0	36
Bilbao	15.0	48	15.0	50	15.0	53	15.0	58	24.6	39	27.1	40	29.5	41	29.8	42	28.3	41	25.3	41	15.0	61	15.0	53
Brescia	15.0	33	15.0	32	15.0	40	15.0	51	26.5	32	30.0	32	30.0	35	30.0	36	28.5	34	15.0	63	15.0	46	15.0	36
Brussels	15.0	38	15.0	38	15.0	44	15.0	51	15.0	70	25.0	43	27.0	45	30.0	54	24.5	47	15.0	63	15.0	46	15.0	41
Bucharest	15.0	26	15.0	29	15.0	36	15.0	49	26.2	35	29.7	35	30.0	36	30.0	34	26.4	34	15.0	55	15.0	44	15.0	32
Budapest	15.0	27	15.0	31	15.0	37	15.0	48	26.1	34	29.2	35	30.0	36	30.0	36	26.4	37	15.0	57	15.0	42	15.0	32
Catania	15.0	55	15.0	54	15.0	58	15.0	67	27.4	38	30.0	40	30.0	48	30.0	52	30.0	45	28.7	41	24.5	42	15.0	62
Copenhagen	15.0	31	15.0	31	15.0	34	15.0	45	15.0	56	25.5	38	27.5	40	26.5	41	15.0	73	15.0	56	15.0	45	15.0	39
Genoa	15.0	38	15.0	42	15.0	47	15.0	64	26.8	40	30.0	41	30.0	47	30.0	46	30.0	39	26.7	37	15.0	53	15.0	43
Glasgow	15.0	38	15.0	39	15.0	42	15.0	48	15.0	55	15.0	69	24.5	43	24.5	44	15.0	70	15.0	59	15.0	47	15.0	44
Hamburg	15.0	30	15.0	31	15.0	37	15.0	46	15.0	60	26.0	41	27.5	43	27.5	45	15.0	78	15.0	61	15.0	44	15.0	36
Helsinki	15.0	20	15.0	19	15.0	22	15.0	32	15.0	43	15.0	60	27.0	39	25.5	43	15.0	68	15.0	47	15.0	34	15.0	26
Lille	15.0	37	15.0	38	15.0	44	15.0	53	15.0	65	25.0	43	26.5	44	26.5	44	25.0	44	15.0	63	15.0	46	15.0	41
Lisbon	15.0	63	15.0	65	15.0	65	24.6	38	26.9	37	29.7	37	30.0	40	30.0	40	30.0	41	28.0	41	15.0	75	15.0	64
London	15.0	42	15.0	42	15.0	45	15.0	49	15.0	61	25.0	39	27.0	40	26.5	42	24.5	44	15.0	65	15.0	54	15.0	46
Lyon	15.0	36	15.0	38	15.0	47	15.0	53	15.0	67	28.0	38	30.0	37	29.5	38	27.0	43	15.0	66	15.0	51	15.0	39
Madrid	15.0	41	15.0	41	15.0	45	15.0	46	25.0	32	29.9	29	30.0	30	30.0	31	29.8	32	15.0	66	15.0	50	15.0	43
Marseille	15.0	43	15.0	43	15.0	51	15.0	59	26.0	38	30.0	37	30.0	40	30.0	41	29.5	40	24.5	42	15.0	59	15.0	46
Milan	15.0	34	15.0	38	15.0	46	15.0	63	26.1	40	30.0	41	30.0	47	30.0	45	28.4	42	15.0	72	15.0	50	15.0	36
Munich	15.0	25	15.0	29	15.0	35	15.0	44	15.0	61	24.9	42	26.8	41	26.1	42	15.0	70	15.0	52	15.0	38	15.0	29
Naples	15.0	48	15.0	49	15.0	53	15.0	63	26.9	39	30.0	41	30.0	48	30.0	48	30.0	42	26.2	41	15.0	64	15.0	52
Newcastle	15.0	40	15.0	40	15.0	43	15.0	46	15.0	55	15.0	65	25.5	41	26.0	41	15.0	69	15.0	55	15.0	49	15.0	38
Nuremburg	15.0	28	15.0	29	15.0	36	15.0	45	15.0	58	26.0	39	27.5	40	27.0	41	15.0	76	15.0	55	15.0	41	15.0	32
Paris	15.0	41	15.0	40	15.0	47	15.0	53	24.5	38	27.5	39	29.5	40	28.5	41	26.0	44	15.0	69	15.0	54	15.0	44
Prague	15.0	26	15.0	28	15.0	34	15.0	43	15.0	60	25.1	39	26.6	39	26.1	40	15.0	69	15.0	52	15.0	38	15.0	30
Rennes	15.0	47	15.0	46	15.0	52	15.0	56	15.0	72	26.6	43	28.7	43	28.5	44	26.0	46	15.0	76	15.0	58	15.0	50
Rome	15.0	46	15.0	49	15.0	53	15.0	64	26.8	40	30.0	41	30.0	48	30.0	48	30.0	42	26.0	42	15.0	62	15.0	50
Rotterdam	15.0	39	15.0	38	15.0	46	15.0	49	15.0	63	24.5	44	26.5	44	26.5	45	15.0	79	15.0	66	15.0	49	15.0	46
Sofia	15.0	25	15.0	28	15.0	35	15.0	47	15.0	65	27.5	38	29.3	36	30.0	36	25.6	36	15.0	53	15.0	40	15.0	30
Stockholm	15.0	25	15.0	23	15.0	28	15.0	36	15.0	49	25.1	37	26.7	40	25.7	42	15.0	66	15.0	51	15.0	38	15.0	29
Toulouse	15.0	41	15.0	37	15.0	43	15.0	49	15.0	60	28.0	33	30.0	33	30.0	33	28.0	35	15.0	60	15.0	52	15.0	43
Turin	15.0	34	15.0	32	15.0	42	15.0	50	27.5	37	30.0	32	30.0	35	30.0	36	28.5	34	15.0	64	15.0	46	15.0	36
Warsaw	15.0	24	15.0	26	15.0	32	15.0	45	15.0	62	26.2	39	27.5	42	26.8	41	15.0	68	15.0	52	15.0	39	15.0	30
Vienna	15.0	25	15.0	27	15.0	34	15.0	48	15.0	64	28.0	37	29.5	36	29.0	38	25.0	41	15.0	58	15.0	41	15.0	31

15.5 Metro stations: Complementary graphs

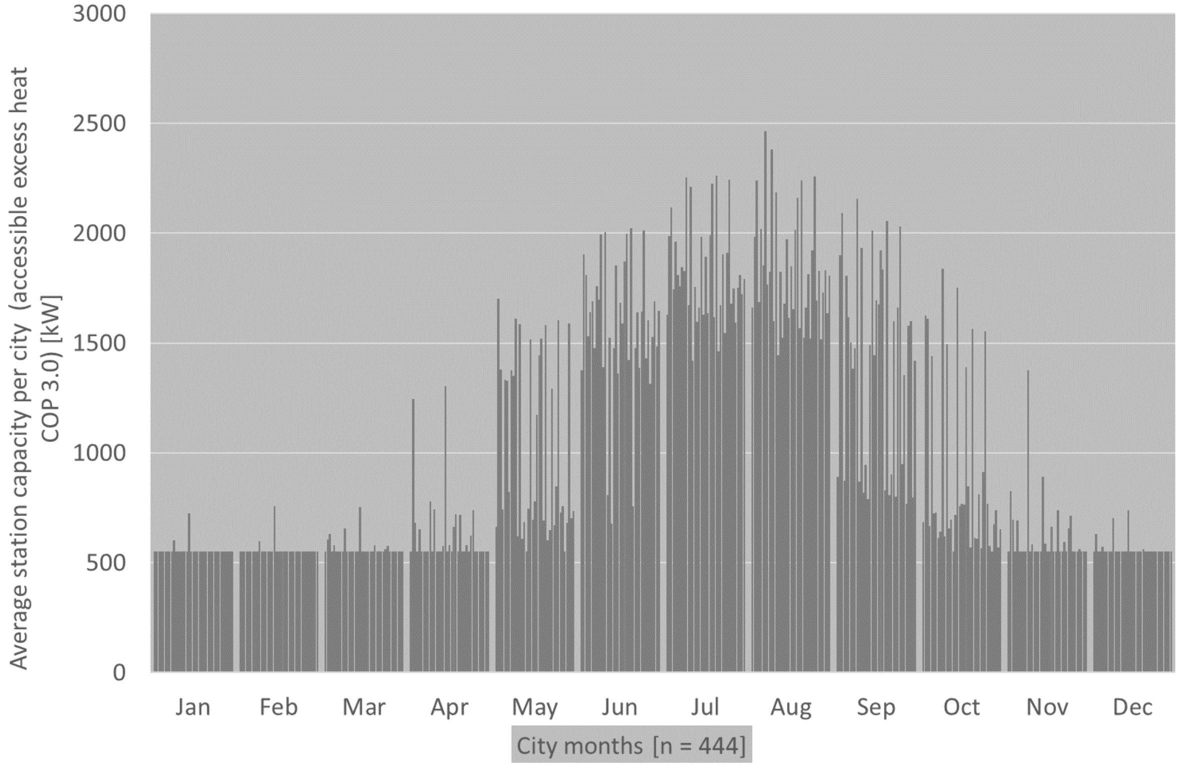

Figure 40. Average monthly station capacities per city for accessible excess heat at practical COP of 3.0 for all 37 studied metro cities.

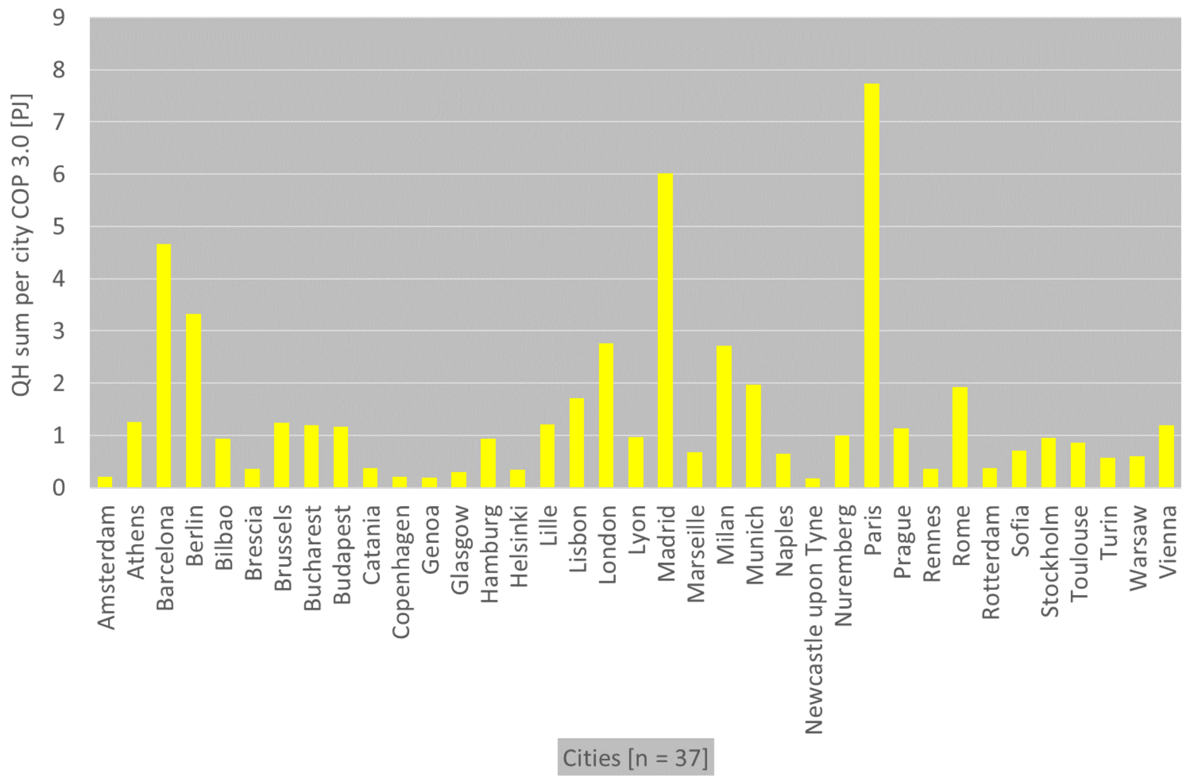

Figure 41. Summation of accessible excess heat per metro city at practical COP of 3.0 (all cities).

15.6 Metro stations: Q_H at COP 2.5 and COP 3.5

Table 60. Number of EU28 metro stations and accessible excess heat inside or within 2 kilometres of urban district heating areas at practical COP of 2.5 and 3.5

MS	Metro stations (2km) [n]	QH COP 2.5 (2km) [PJ/a]	QH COP 3.5 (2 km) [PJ/a]
AT	48	1.3	1.1
BE	47	1.4	1.2
BG	29	0.8	0.7
CZ	53	1.3	1.1
DE	318	8.0	6.7
DK	9	0.2	0.2
ES	370	11.7	9.8
FI	17	0.4	0.3
FR	419	12.4	10.4
HU	44	1.3	1.1
IT	185	6.4	5.4
NL	25	0.6	0.5
PL	27	0.7	0.6
PT	48	1.9	1.6
RO	45	1.3	1.1
SE	45	1.1	0.9
UK	125	3.3	2.7
EU28	**1854**	**54.0**	**45.4**

15.7 Food production: Calculation example**

Danish branch factor for electricity intensity weight					
NACE3	Danish industry branch	Facilities [n]	Total electricity consumption [TJ/year]	Electricity consumption per facility [TJ/fac]	Electricity intensity branch factor
C101	Slaughtering	89	1336	15.0112	0.68
C102	Fish processing	65	303	4.6615	0.21
C103	Other food products	38	127	3.3421	0.15
C104	Other food products	304	1136	3.7368	0.17
C105	Dairy	67	1479	22.0746	1.00
C106	Other food products	304	1136	3.7368	0.17
C107	Bakery	90	332	3.6889	0.17
C108	Other food products	86	556	6.4651	0.29
C109	Animal feeds	56	764	13.6429	0.62
C110	Beverage	38	542	14.2632	0.65
C120	Tobacco	7	30	4.2857	0.19
*Kortlægning af energiforbrug i virksomheder, using 2012 data					

INPUT	
(#) Number in process	

Yearly national electricity consumption C10-C12 [PJ/2017]	8.68

Weighted sizing total SUM C10-C12	1284.63

DK-C101								
Facility size (# of employees)	Facilities [n]	Sizing factor	Electricity intensity branch factor	Weighted sizing factor per facility (1)	Weighted sizing total (2)	C10-C12 share (3)	Categorized electricity consumption by size (4)	National averaged facility electricity consumption (5)
0-9	81	1	0.68	0.68	55.08	4.29%	0.37	0.015
10-19	9	2		1.36	12.24	0.95%	0.08	
20-49	22	4		2.72	59.84	4.66%	0.40	
50-249	9	8		5.44	48.96	3.81%	0.33	
>250	11	16		10.88	119.68	9.32%	0.81	
Σ	132						2.00	

Figure 42. National averaged facility electricity consumption; calculation example for DK's NACE3-C101: Processing and preserving of meat and production of meat products.

15.8 Food production: Q_H at COP 2.5 and COP 3.5**

Table 61. Spatial (left) and non-spatial (right) food production facilities: available (QL) and accessible heat recovery potentials (QH) at COP 2.5, COP 3.0, and COP 3.5

MS	Facilities [n]	QL [PJ]	QH COP2.5 [PJ]	QH COP3.0 [PJ]	QH COP3.5 [PJ]
AT	19	0.08	0.13	0.12	0.11
BE	111	0.77	1.28	1.15	1.08
BG	5	0.00	0.00	0.00	0.00
HR	16	0.02	0.04	0.03	0.03
CY	0	0	0	0	0
CZ	52	0.02	0.03	0.03	0.03
DK	31	0.50	0.84	0.75	0.70
EE	4	0.02	0.04	0.04	0.03
FI	24	0.28	0.47	0.43	0.40
FR	493	1.80	3.01	2.71	2.53
DE	321	1.67	2.79	2.51	2.34
EL	6	0.00	0.00	0.00	0.00
HU	36	0.11	0.19	0.17	0.16
IE	66	1.02	1.70	1.53	1.43
IT	184	0.29	0.48	0.43	0.41
LV	1	0.00	0.01	0.00	0.00
LT	9	0.07	0.11	0.10	0.09
LU	1	0.01	0.02	0.02	0.01
MT	0	0	0	0	0
NL	147	1.19	1.99	1.79	1.67
PL	166	0.56	0.93	0.84	0.79
PT	42	0.07	0.11	0.10	0.09
RO	27	0.06	0.09	0.09	0.08
SK	13	0.01	0.02	0.02	0.02
SI	8	0.01	0.01	0.01	0.01
ES	276	0.61	1.02	0.92	0.86
SE	39	0.17	0.29	0.26	0.24
UK	390	2.56	4.27	3.84	3.58
EU28	**2,487**	**11.93**	**19.89**	**17.90**	**16.71**

MS	Facilities [n]	QL [PJ]	QH COP2.5 [PJ]	QH COP3.0 [PJ]	QH COP3.5 [PJ]
AT	3,959	7.76	12.93	11.64	10.86
BE	7,122	21.43	35.71	32.14	30.00
BG	6,159	4.33	7.22	6.50	6.07
HR	3,253	2.30	3.83	3.45	3.22
CY	771	0.58	0.97	0.87	0.82
CZ	2,243	3.56	5.93	5.34	4.98
DK	1,644	8.57	14.28	12.85	11.99
EE	737	1.15	1.92	1.73	1.61
FI	1,749	6.84	11.40	10.26	9.58
FR	55,144	72.03	120.04	108.04	100.84
DE	23,451	76.78	127.96	115.16	107.49
EL	16,420	3.00	5.00	4.50	4.20
HU	6,762	8.09	13.49	12.14	11.33
IE	1,348	9.54	15.90	14.31	13.35
IT	55,655	39.33	65.55	59.00	55.07
LV	1,196	1.11	1.86	1.67	1.56
LT	1,627	3.01	5.02	4.52	4.22
LU	158	0.48	0.81	0.73	0.68
MT	0	0	0	0	0
NL	6,629	23.88	39.80	35.82	33.43
PL	15,202	27.44	45.73	41.16	38.41
PT	11,218	6.14	10.23	9.20	8.59
RO	9,143	6.60	11.00	9.90	9.24
SK	3,720	1.46	2.44	2.19	2.05
SI	2,481	1.15	1.92	1.73	1.61
ES	28,248	38.07	63.46	57.11	53.30
SE	4,488	8.81	14.68	13.21	12.33
UK	9,982	39.76	66.26	59.63	55.66
EU28	**280,509**	**423.21**	**705.34**	**634.81**	**592.49**

Table 62. Number of georeferenced EU28 food production facilities, available and accessible excess heat (at practical COP 2.5 and 3.5) inside or within 2 kilometres of urban district heating areas

MS	**Facilities (2km) [n]**	**QL (2km) [PJ]**	**QH COP2.5 (2km) [PJ]**	**QH COP3.5 (2km) [PJ]**
AT	14	0.05	0.09	0.08
BE	68	0.43	0.72	0.61
CZ	31	0.01	0.02	0.02
DE	77	0.33	0.55	0.47
DK	23	0.35	0.59	0.50
EE	3	0.02	0.03	0.02
ES	21	0.05	0.09	0.07
FI	19	0.23	0.39	0.32
FR	92	0.34	0.57	0.48
HR	10	0.02	0.03	0.02
HU	24	0.10	0.17	0.15
IE	5	0.03	0.05	0.04
IT	25	0.04	0.06	0.05
LT	3	0.02	0.04	0.03
LV	1	0.00	0.01	0.00
NL	32	0.17	0.28	0.24
PL	91	0.31	0.52	0.44
PT	4	0.00	0.00	0.00
RO	13	0.02	0.04	0.03
SE	28	0.12	0.20	0.17
SI	5	0.01	0.01	0.01
SK	12	0.01	0.02	0.02
UK	98	0.49	0.82	0.69
EU28	**699**	**3.18**	**5.31**	**4.46**

15.9 Food retail: List of EU28 food retail chains**

Table 63. Food retail chains in EU28 based on [277]

Code	Name	Code	Name	Code	Name	Code	Name
AT	basic	EE	delice food store	IE	eurospar	NL	poiesz
AT	billa	EE	grossi toidukaubad	IE	fresh	NL	spar
AT	denns biomarkt	EE	maxima	IE	iceland	NL	until 2020
AT	etsan	EE	meie toidukaubad	IE	joyces	NL	vomar
AT	hofer	EE	prisma peremarket	IE	lidl	PL	abc
AT	lidl	EE	rimi	IE	marks & spencer	PL	aldi
AT	maximarkt	EE	r-kiosk	IE	supervalu	PL	arhelan
AT	merkur	EE	selver	IE	tesco	PL	biedronka
AT	metro	EE	stockmann	IT	a&o	PL	chata polska
AT	mpreis	EE	toidumaailm	IT	aldi	PL	chorten
AT	nah & frisch	EL	ab	IT	auchan	PL	dino
AT	norma	EL	aldi	IT	bennet	PL	frac
AT	penny markt	EL	arista	IT	carrefour	PL	freshmarket
AT	spar	EL	bazaar	IT	conad	PL	groszek
AT	sutterlüty	EL	carrefour	IT	coop	PL	intermarché
AT	unimarkt	EL	cba	IT	crai	PL	lewiatan
BE	ad delhaize	EL	dia	IT	despar	PL	lidl
BE	albert heijn	EL	galaxias	IT	dok	PL	livio
BE	aldi	EL	lidl	IT	dpiù	PL	mila
BE	bio-planet	EL	masoutis	IT	esselunga	PL	minuta 8
BE	carrefour	EL	my market	IT	eurospin	PL	netto
BE	carrefour express	EL	spar	IT	famila	PL	odido
BE	carrefour market	ES	ahorramás	IT	il gigante	PL	piotr i paweł
BE	colruyt	ES	alcampo	IT	ins mercato	PL	polomarket
BE	cora	ES	aldi	IT	iper	PL	rabat detal
BE	delhaize	ES	auchan	IT	lidl	PL	rosa
BE	intermarché	ES	barcelona market	IT	margherita	PL	spar
BE	leader price	ES	caprabo	IT	md	PL	społem
BE	lidl	ES	captura	IT	mpreis	PL	stokrotka
BE	makro	ES	carrefour	IT	pam	PL	top market
BE	match	ES	carrefour	IT	panorama	PL	żabka
BE	okay	ES	consum	IT	penny market	PT	aldi
BE	proxy delhaize	ES	dia	IT	prix	PT	amanhecer
BE	shop & go	ES	e.leclerc	IT	sigma	PT	apolonia supermercados
BE	spar	ES	eroski	IT	simply market	PT	auchan
BG	billa	ES	froiz	IT	sisa	PT	continente
BG	cba	ES	gadis	IT	supeco	PT	coviran
BG	fantastico	ES	hipercor	IT	todis	PT	e.leclerc
BG	hit	ES	ifa	IT	tuodì	PT	el corte inglés
BG	kam market	ES	lidl	IT	unes	PT	froiz
BG	kaufland	ES	makro	LT	aibė	PT	intermarché
BG	lidl	ES	mercadona	LT	cba	PT	lidl
BG	metro	ES	sánchez romero	LT	čia market	PT	mercadona
BG	promarket	ES	spar	LT	express market	PT	meu super
BG	t market	ES	supercor	LT	gastronomas rūpestėlis	PT	minipreço
BG	triumf	ES	supersol	LT	grūstė	PT	pingo doce
CY	alphamega	ES	zara	LT	iki	PT	spar
CY	e&s	FI	alepa	LT	kubas	RO	auchan
CY	lidl	FI	alko	LT	lidl	RO	carrefour
CY	metro	FI	k-citymarket	LT	maxima	RO	carrefour contact
CY	olympic	FI	k-market	LT	narvesen	RO	carrefour express
CY	sklavenitis	FI	k-supermarket	LT	norfa	RO	carrefour market
CY	spar	FI	lidl	LT	rimi	RO	cora
CZ	albert	FI	m-market	LT	šilas	RO	kaufland
CZ	billa	FI	prisma	LT	solo	RO	lidl
CZ	globus	FI	r-kioski	LT	tau	RO	mega image
CZ	kaufland	FI	sale	LU	aldi	RO	metro
CZ	lidl	FI	s-market	LU	alima	RO	myauchan
CZ	makro	FI	stockmann	LU	auchan	RO	penny market
CZ	norma	FI	tokmanni	LU	cactus	RO	profi
CZ	penny market	FR	aldi	LU	carrefour	RO	selgros
CZ	tesco	FR	auchan	LU	colruyt	RO	shop&go
DE	aldi nord	FR	auchan	LU	cora	RO	supeco

DE	aldi süd	FR	carrefour	LU	delhaize	SE	7-eleven
DE	alnatura	FR	carrefour	LU	lidl	SE	city gross
DE	bio	FR	carrefour	LU	match	SE	coop
DE	cap markets	FR	casino	LU	monoprix	SE	eko
DE	edeka	FR	casino shop	LU	naturata	SE	handlarn
DE	globus	FR	colruyt	LU	pall center	SE	hemköp
DE	kaisers	FR	cora	LU	proxy	SE	ica kvantum
DE	kaufland	FR	e. leclerc	LU	rewe	SE	ica maxi stormarknad
DE	kaufpark	FR	express u	LU	smatch	SE	ica nära
DE	lidl	FR	franprix	LU	thymcitron	SE	ica supermarket
DE	metro cash and carry	FR	géant casino	LV	aibė	SE	lidl
DE	netto	FR	hyper u	LV	beta	SE	matöppet
DE	netto marken-discount	FR	intermarché	LV	elvi	SE	matrebellerna
DE	norma	FR	leader price	LV	maxima	SE	netto
DE	penny markt	FR	leader price express	LV	mego	SE	pressbyrån
DE	real	FR	lidl	LV	rimi	SE	tempo
DE	rewe	FR	match	LV	sky	SE	willys
DE	selgros	FR	metro cash and carry	LV	top!	SI	e.leclerc
DE	spar	FR	monoprix	LV	vesko	SI	hofer
DE	tegut...	FR	netto	MT	auchan	SI	lidl
DK	7-eleven	FR	norma	MT	carrefour	SI	mercator
DK	aldi	FR	petit casino	MT	conad	SI	spar
DK	bilka	FR	spar	MT	lidl	SK	billa
DK	daglibrugsen	FR	super u	MT	pavi supermaket	SK	cba
DK	døgnnetto	FR	utile	MT	scotts supermarket	SK	coop jednota slovakia
DK	fakta	FR	vival	MT	spar	SK	fresh
DK	faktaq	HR	cba	MT	towers supermarket	SK	kaufland
DK	føtex	HR	kaufland	NL	agrimarkt	SK	lidl
DK	irma	HR	konzum	NL	albert heijn	SK	moj obchod
DK	irma city	HR	lidl	NL	aldi	SK	terno
DK	kiwi	HR	metro	NL	attent	SK	tesco
DK	kvickly	HR	spar	NL	boni	UK	aldi
DK	let-køb	HU	ab	NL	coop	UK	asda
DK	lidl	HU	aldi	NL	dagwinkel	UK	booths
DK	lokalbrugsen	HU	auchan	NL	deen	UK	budgens
DK	løvbjerg	HU	cba	NL	dekamarkt	UK	farmfoods
DK	meny	HU	coop	NL	dirk	UK	fultons foods
DK	min købmand	HU	dm-drogerie markt	NL	ekoplaza	UK	heron foods
DK	netto	HU	lidl	NL	hoogvliet	UK	iceland
DK	rema 1000	HU	penny market	NL	jan linders	UK	jacks
DK	spar	HU	reál	NL	jumbo	UK	lidl
DK	superbrugsen	HU	rossmann	NL	lidl	UK	marks & spencer
EE	aldar market	HU	spar	NL	marqt	UK	morrisons
EE	comarket	HU	tesco	NL	mcd	UK	ocado
EE	coop konsum	IE	aldi	NL	nettorama	UK	sainsburys
EE	coop maksimarket	IE	donnybrook fair	NL	picnic	UK	tesco
EE	coop väikepood	IE	dunnes stores	NL	plus	UK	waitrose

15.10 Food retail: Model input**

Table 64. Monthly and yearly average outdoor temperatures [°C] from 2015 by country with data from [4]

MS	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
FI	-7.7	-8.9	-4.6	2.3	8.2	12.8	16.5	14.4	8.9	3.1	-2.2	-5.7	3.2
SE	-3.8	-4.5	-1.6	4.2	9.5	13.6	16.6	15.5	10.6	5.2	0.6	-2.5	5.3
EE	-3.0	-4.4	-1.0	5.6	11.1	14.5	18.4	17.0	11.9	6.8	2.0	-1.6	6.5
LV	-2.1	-3.0	0.3	6.3	11.6	14.7	18.4	17.4	12.4	7.4	2.9	-0.4	7.2
LT	-2.1	-1.9	1.8	8.0	13.3	15.9	19.1	18.3	13.2	8.4	3.7	-0.4	8.2
PL	-1.6	-0.9	2.2	8.1	13.3	15.8	18.7	18.0	13.1	8.6	3.9	-0.1	8.3
CZ	-1.6	0.0	3.2	8.7	13.7	16.4	18.2	18.1	13.1	8.9	4.0	-0.4	8.6
DK	1.4	1.2	3.2	7.5	11.6	14.5	17.6	17.3	13.8	9.4	5.6	2.2	8.8
SK	-2.5	-0.7	3.5	9.6	14.8	17.3	19.6	19.0	13.5	9.3	4.2	-0.8	9.0
SI	-0.5	0.8	4.6	8.8	14.1	17.2	19.0	18.6	13.5	10.3	5.3	0.8	9.4
DE	1.1	1.8	4.4	8.9	13.5	16.2	18.2	17.9	13.9	9.9	5.3	1.8	9.4
UK	5.0	4.8	6.3	8.4	11.5	14.0	15.8	15.8	13.6	10.7	7.5	4.9	9.9
LU	1.3	2.6	5.5	9.6	14.0	16.8	18.4	18.1	14.2	10.4	5.6	2.1	9.9
AT	-1.3	1.3	5.4	10.5	15.7	18.4	19.9	19.4	14.5	10.3	4.7	0.0	10.0
BE	2.7	3.5	5.8	9.2	13.3	15.8	17.5	17.3	14.2	10.8	6.6	3.1	10.0
IE	6.2	6.0	7.3	8.7	11.4	13.6	15.0	15.1	13.5	11.0	8.2	6.4	10.2
NL	4.1	4.2	5.9	9.4	13.1	15.5	17.7	17.9	15.1	11.5	7.8	4.2	10.6
HU	-0.6	1.3	6.0	12.0	17.3	19.8	21.9	21.4	15.7	11.3	5.7	0.6	11.1
RO	-0.9	1.1	6.2	11.4	17.4	20.4	23.0	22.6	16.6	11.8	6.2	0.6	11.4
IT	2.8	3.6	7.2	10.0	15.4	19.3	21.8	21.5	16.3	13.1	7.6	3.8	11.9
BG	0.6	2.6	7.2	11.4	17.0	20.7	23.6	23.3	17.7	13.2	7.4	2.1	12.3
FR	5.8	6.5	8.9	11.4	15.4	18.9	20.6	20.5	17.1	14.0	9.2	6.0	12.9
PT	8.4	9.5	11.7	12.7	16.0	19.8	21.2	21.7	19.3	15.9	11.2	9.0	14.7
HR	5.1	6.3	10.0	14.3	19.7	22.8	25.4	25.0	19.2	15.6	10.5	6.3	15.1
ES	8.6	9.7	12.4	13.7	17.6	21.8	23.8	23.9	20.5	17.0	11.7	9.1	15.9
EL	7.0	7.7	11.0	14.1	19.3	23.6	26.6	26.3	21.5	17.5	12.3	8.5	16.3
MT	12.4	11.8	13.7	15.5	19.7	23.4	26.6	26.5	23.6	21.1	17.3	14.3	18.9
CY	12.3	12.4	14.7	17.5	21.7	25.2	28.0	28.1	25.4	22.7	17.7	14.0	20.0

Table 65. Opening hours by country and food retail size category. Sources: [278, 279]

MS	Cat1			Cat2			Cat3			Cat4			Cat5			Week
	M-F	Sa	Su	M-F	Sa	Su	M-F	Sa	Su	M-F	Sa	Su	M-F	Sa	Su	
AT	12	10	0	13	10	0	12	10	0	16	16	16	16	16	16	11
BE	11	11	11	11	11	0	12	12	0	12	12	7	12	12	7	9
BG	14	14	14	14	14	13	15	15	15	16	16	16	16	16	16	15
HR	13	14	7	13	13	13	14	14	14	13	13	13	13	13	13	13
CY	14	14	12	14	14	13	13	7	7	13	13	10	13	13	10	12
CZ	13	13	13	13	13	13	15	15	15	13	13	12	13	13	12	13
DK	8	8	0	13	13	0	15	15	15	14	14	14	14	14	14	11
EE	8	8	8	14	14	14	14	14	14	14	14	14	14	14	14	13
FI	13	13	10	13	13	10	17	17	14	14	14	14	14	14	14	14
FR	12	12	0	15	15	4	12	12	4	13	13	13	13	13	13	11
DE	15	15	0	15	15	0	15	15	0	14	14	12	14	14	12	11
EL	13	13	0	13	13	0	13	13	0	13	13	13	13	13	13	10
HU	15	15	11	15	15	10	15	13	12	15	15	11	15	15	11	13
IE	14	14	14	14	14	12	15	15	13	12	12	9	12	12	9	13
IT	11	11	0	12	12	4	12	12	11	13	13	11	14	14	12	11
LV	14	14	14	16	16	16	16	16	16	14	14	14	14	14	14	15
LT	14	14	14	16	16	16	16	16	16	14	14	14	14	14	14	15
LU	13	13	5	11	11	4	11	11	6	13	13	9	13	13	9	10
MT	14	14	14	14	14	12	14	14	12	15	15	15	15	15	15	14
NL	12	12	12	15	15	15	15	15	15	14	14	12	14	14	12	14
PL	15	15	0	14	14	9	14	14	9	17	17	17	17	17	17	14
PT	13	13	13	12	12	12	12	12	12	15	15	15	15	15	15	13
RO	14	14	14	14	14	13	15	15	15	16	16	16	16	16	16	15
SK	14	14	14	16	16	16	16	16	16	14	14	14	14	14	14	15
SI	13	14	7	13	13	13	14	14	14	13	13	13	13	13	13	13
ES	13	13	13	12	12	12	12	12	12	15	15	15	15	15	15	13
SE	8	8	0	13	13	0	15	15	15	14	14	14	14	14	14	11
UK	13	14	7	13	13	13	14	14	14	13	13	13	13	13	13	13

15.11 Service sector: Q_H at COP 2.5 and COP 3.5

Table 66. Service sector accessible excess heat inside urban district heating areas at practical COP of 2.5 and 3.5

MS	QH (inside) COP 2.5 [PJ]	QH (inside) COP 3.5 [PJ]
AT	3.1	2.6
BE	9.2	7.7
BG	6.5	5.5
CY	0	0
CZ	1.9	1.6
DE	29.4	24.7
DK	2.1	1.8
EE	1.6	1.4
EL	-	-
ES	65.9	55.4
FI	2.4	2.0
FR	55.7	46.8
HR	2.8	2.4
HU	4.5	3.8
IE	0.5	0.4
IT	76.6	64.3
LT	0.4	0.4
LU	0.1	0.1
LV	0.3	0.2
MT	0	0
NL	2.6	2.2
PL	8.8	7.4
PT	5.3	4.5
RO	8.7	7.3
SE	6.0	5.0
SI	1.8	1.5
SK	0.8	0.6
UK	26.8	22.5
EU28	**323.9**	**272.1**

15.12 Residential sector: Q_H at COP 2.5 and COP 3.5**

Table 67. Residential sector accessible excess heat inside urban district heating areas at practical COP of 2.5 and 3.5

MS	QH COP 2.5 (2015 e>=1) (inside) [PJ]	QH COP 3.5 (2015 e>=1) (inside) [PJ]
AT	5.4	4.5
BE	1.4	1.2
BG	5.5	4.6
CY	0	0
CZ	0.5	0.5
DE	4.2	3.5
DK	0.7	0.6
EE	0.5	0.4
EL	-	-
ES	29.3	24.6
FI	0.2	0.1
FR	11.8	9.9
HR	0.03	0.02
HU	1.6	1.4
IE	0.01	0.01
IT	49.1	41.2
LT	0.3	0.2
LU	0.02	0.01
LV	0.02	0.01
MT	0	0
NL	0.1	0.1
PL	3.2	2.6
PT	0.2	0.2
RO	4.3	3.6
SE	2.6	2.2
SI	0.02	0.02
SK	0.01	0.01
UK	0.9	0.7
EU28	**121.9**	**102.4**

15.13 Waste water: Q_H at COP 2.5 and COP 3.5

Table 68. Number of EU28 urban waste water treatment plants and accessible excess heat inside or within 2 kilometres of urban district heating areas at practical COP of 2.5 and 3.5

MS	**UWWT plants (2km) [n]**	**QH (R4) COP 2.5 (2km) [PJ]**	**QH (R4) COP 3.5 (2km) [PJ]**
AT	231	26.5	22.3
BE	218	15.8	13.3
BG	13	6.6	5.6
CZ	369	22.0	18.5
DE	418	134.7	113.1
DK	199	16.2	13.6
EE	45	3.8	3.2
EL	3	0.3	0.2
ES	57	25.0	21.0
FI	106	13.5	11.3
FR	597	95.1	79.8
HR	12	4.4	3.7
HU	113	17.9	15.0
IE	6	6.6	5.6
IT	194	44.3	37.2
LT	33	5.6	4.7
LU	5	0.6	0.5
LV	35	3.3	2.8
NL	64	17.0	14.3
PL	445	74.2	62.3
PT	14	4.2	3.5
RO	76	20.2	17.0
SE	232	22.6	18.9
SI	42	2.1	1.8
SK	153	8.3	7.0
UK	302	103.5	86.9
EU28	**3982**	**694.3**	**583.2**