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Unlocking waste heat potential for district heating systems: an hourly mapping methodology

Andrea Menapace^{a*}, Daniele Anania^{a,d}, Giovanni Dalle Nogare^a, Rosanna Paradiso^a, Marco Cozzini^a, Diana Moreno^b, Steffen Nielsen^b, Peter Sorknæs^b, Ernst Gebetsroither-Geringer^c, Anna Kozłowska^c

^aInstitute for Renewable Energy, Eurac Research, Viale Druso 1, 39100 Bolzano, Italy

^bDepartment of Sustainability and Planning, Aalborg University, Rendsburggade 14, 9000 Aalborg, Denmark

^cAIT Austrian Institute of Technology, Giefinggasse 4, 1210 Vienna, Austria

^dEnergy Department, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129, Torino, Italy

ABSTRACT

The transition towards climate-neutral energy systems requires exploiting local renewable and residual energy sources to decarbonise the heating and cooling sector. District heating (DH) is a key infrastructure for integrating waste heat (WH) into urban energy systems, but comprehensive spatial data on WH availability are often lacking and difficult to retrieve. This study develops a methodology for mapping WH potential from both industrial and tertiary sectors, providing critical information for the decarbonisation and expansion of existing DH systems, as well as for the development of new DH systems. The approach combines open geographic datasets, statistical information and literature-based coefficients within a structured workflow to estimate potential annual WH availability at different temperature levels, along with its hourly profiles. The outcome is a detailed spatio-temporal characterisation of WH, presented in a geospatial package containing the georeferenced annual WH potential, coupled with a dataset of hourly profiles for each activity during a typical meteorological year. The methodology is applied to a case study in Milan with three main objectives: first, to test and validate the reliability of the proposed approach; second, to discuss the implications of WH integration in the development of a DH modernisation scenario; and third, to assess the uncertainty of waste heat potential estimation through comparison with Danish and Austrian reference databases. Thus, this study offers a replicable framework for WH potential mapping, supporting planning and decision-making for the sustainable development of DH as part of broader urban energy transition strategies.

Keywords

Waste heat;
Energy mapping;
Decarbonisation;
Energy transition;
District heating

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1. Introduction

The transition towards climate-neutral and renewable-based energy systems requires a profound transformation of how energy is produced, distributed and consumed [1,2]. Achieving high shares of renewable energy sources (RES) demands the integration of multiple sectors, i.e., electricity, heating, cooling, transport, including also industry, within a unified framework able to exploit cross-sectoral synergies and enhance overall efficiency [3,4]. In this context, the concept of smart energy systems (SES) has emerged as a paradigm shift

from electricity-centric “smart grids” to multi-sector integrated systems that coordinate smart electricity, thermal and gas grids [5,6]. Such integration provides the flexibility required to balance the intermittency of wind and solar generation by exploiting thermal storage, power-to-heat conversion and sector coupling, thus reducing dependence on fossil-fuelled plants that have traditionally supplied system flexibility [7,8].

Within SES, district heating (DH) plays a crucial systemic role as an effective infrastructure capable of coupling different energy carriers and integrating renewable

*Corresponding author – e-mail: andrea.menapace@eurac.edu

and recovering residual heat [9]. By connecting diverse sources, such as geothermal, solar thermal, waste-to-energy and industrial excess heat, with urban demand centres, DH acts as a thermal backbone that enables the efficient use of local resources, reduces primary energy consumption and supports the integration of variable renewables [10]. The continuous development of these networks has been described through successive technological “generations”.

The first to third generations were based on steam and high-temperature pressurised water, designed for fossil-fuel-dominated systems. In particular, third-generation district heating (3GDH) is characterised by relatively high network temperatures, typically in a range that enables the direct utilisation of high-temperature heat sources and conventional thermal generation technologies, but at the same time constrains the direct recovery of low-temperature waste heat because of the larger temperature lift required for network integration [11]. As a result, in 3GDH systems, the feasibility of waste heat utilisation is generally restricted to sources available at sufficiently high temperatures or requires additional upgrading technologies. The fourth-generation district heating (4GDH) concept represents a major innovation, characterised by low supply temperatures, reduced distribution losses and compatibility with energy-efficient buildings [12]. Crucially, 4GDH integrates DH into smart energy systems, linking them with electricity and gas grids to facilitate system-wide flexibility and cost-optimal decarbonisation. From a waste heat integration perspective, this temperature reduction is highly relevant, since recent Danish heat planning studies have shown that temperature thresholds around 80 °C and 60 °C provide a useful screening basis to distinguish sources that are more readily utilisable in 3GDH and 4GDH, respectively, while lower-temperature sources generally require upgrading by heat pumps [11,13]. This is particularly important because the transition from 3GDH to 4GDH expands the technical potential for WH recovery, enabling the utilisation of a wider range of low- and medium-temperature sources that would otherwise remain difficult to exploit in higher-temperature networks.

More recently, fifth-generation district heating and cooling (5GDHC) has emerged as a complementary approach. 5GDHC networks operate at ambient loop temperatures (10–30 °C), employ bidirectional flow and distributed heat pumps and are particularly suited to areas with simultaneous heating and cooling demands.

This configuration enables direct recovery of very-low-temperature WH from data centres, supermarkets and tertiary buildings, further expanding the range of directly usable renewable and residual sources [14]. While 4GDH ensures system-level optimisation, 5GDHC enhances local energy exchange and enables new business models for prosumers.

In this broader energy transition, WH recovery emerges as a crucial yet underexploited opportunity [15]. WH sources are categorised as RES according to the Energy Efficiency Directive (EED) [16], which can be utilised directly, when its temperature matches DH requirements, or indirectly, when upgraded through heat pumps to usable levels [17–20]. Integrating WH into DH offers significant environmental and economic benefits: it reduces fossil-fuel demand, limits the use of scarce biomass resources, while lowering greenhouse-gas emissions with increasing system efficiency and flexibility [21,22]. However, despite its large technical potential, the actual recovery and use of waste heat remain limited, mainly due to insufficient awareness of available sources and their characteristics [23,24].

Accurate identification, estimation and characterisation of WH are therefore essential for DH modelling, simulation and strategic planning [25–28]. Reliable data on the location, quantity and temperature of residual heat potential are prerequisites for evaluating technical and economic feasibility, prioritising connections and designing modernisation strategies for existing and new DH [29,30]. Existing studies often rely on low temporal-resolution or spatially aggregated results [31–33], lacking the detail required for robust and reliable WH assessment and decision-making. Other studies provide more detailed analyses but typically focus on only a few specific WH typologies [34–36] or technologies [37–39], thereby preventing a comprehensive evaluation of the full spectrum of WH potential across all sectors. As a result, current literature either lacks fine spatial and temporal granularity or remains limited to selected WH typologies, preventing a comprehensive assessment of the full WH potential across urban and industrial sectors, which is necessary to support DH expansion and modernisation in line with EED principles. A noteworthy contribution in this context is the Pan-European Thermal Atlas (Peta) [40], which offers harmonised, large-scale mapping of heat demand, DH potential and selected WH sources across Europe. However, its coarse spatial resolution, absence of temporal profiles, limited detail in some areas and the omission of certain WH source

categories, especially within the tertiary sector, limit its suitability for urban-scale analyses.

To address this gap, this work proposes to extend existing energy atlases through an efficient and systematic workflow capable of augmenting them with detailed urban WH information, easily expandable to new source categories and enriched with hourly temperature and availability profiles. Such an approach enables both comprehensive screening at the municipal scale and detailed case-by-case assessments for integration into DH systems planning. Building on this framework, the present study develops a replicable methodology to quantify, map and characterise WH availability from industrial and tertiary sectors, like supermarkets, shopping malls and hospitals. The workflow combines open geographic data, statistical information and literature-based coefficients to estimate annual WH potentials at different temperature levels and derive hourly profiles for each activity type. The methodology is demonstrated through an application to the Milan metropolitan area, pursuing three objectives: (i) to validate the proposed approach in an urban context; (ii) to assess the implications of WH integration for district-heating modernisation; and (iii) to compare results with reference datasets from Denmark and Austria to evaluate uncertainty and methodological transferability.

By delivering a high-resolution spatio-temporal characterisation of urban and industrial WH resources, this study provides a methodology for energy modelling, planning and decision-support in the design of current and new generation of DH. Although developed in the broader context of DH, the methodology is here demonstrated with specific reference to DH, while also being potentially relevant for 5GDHC providing both heating and cooling. The remainder of the paper is organised as follows: Section 2 presents the methodological framework, Section 3 applies the method to the Milan case study and Section 4 discusses the results. Finally, Section 5 summarises conclusions and future perspectives.

2. Methodology

This section presents the methodology developed to quantify, map and characterise WH potential from both industrial and tertiary sectors. First, Section 2.1 outlines the overall methodological framework, while Section 2.2 outlines the assessment of industrial WH, Section 2.3 details the evaluation of tertiary WH and finally

Section 2.4 presents the energy system analysis used to assess WH integration into a DH.

2.1 Methodology framework

The proposed workflow combines heterogeneous data sources and computational procedures into a unified process for quantifying, mapping and characterising WH potential from both industrial and tertiary activities. The methodology follows a structured sequence that begins with the collection and preprocessing of geospatial and statistical inputs, continues with the estimation of annual WH potential using activity-specific formulations implemented in a QGIS plugin [41] and concludes with the generation of hourly availability profiles, produced through a custom-made Python script, suitable for integration into energy-system models. Industrial WH is estimated through a hybrid approach that combines facility-level data with a reference WH dataset, whereas tertiary WH relies on empirical coefficients applied to building geometry and activity classifications.

2.2 Industrial Waste Heat

2.2.1 Inputs

The identification of potential industrial WH sources relies on a structured data collection process and a series of preprocessing steps designed to ensure consistency, traceability and reproducibility in the WH estimation methodology. This process requires two complementary types of data: a detailed industrial facility dataset describing companies and a reference industrial WH database providing sector- and size-specific coefficients for estimating recoverable heat.

Thus, the first input is a comprehensive list of industrial facilities within the area of interest, typically retrieved from the local Chamber of Commerce or similar institutional sources. For each facility, the dataset should include:

- location (address or coordinates),
- industrial activity type (NACE code, at least 3 digits),
- company size (number of employees).

Once collected, the dataset undergoes a preprocessing workflow, automated via a Python script, to harmonise and prepare the information for WH calculation. The first step consists of data cleaning, addressing duplicated records and correcting cases where multi-site enterprises are reported with repeated employee counts; in such situations, the total number of employees is evenly

distributed across all associated sites to avoid overestimation. Subsequently, a harmonisation procedure ensures compatibility between the NACE codes in the local dataset and the industrial sector classification used in the reference WH database, with the 3-digit NACE level offering the most reliable correspondence. The dataset is then standardised into a uniform tabular structure suitable for automated processing, calculation routines and Geographic Information System (GIS) integration. When necessary, a geocoding step converts facility addresses into geographic coordinates to enable accurate spatial representation. Finally, the processed dataset is subjected to expert validation, where a technical operator verifies the completeness, coherence and plausibility of all entries before the WH estimation is performed.

The second essential input is the Danish industrial WH database, originally compiled by the Technical University of Denmark [42] and later further developed and applied in Danish DH planning studies at Aalborg University [11,13]. This dataset, hereafter referred to as the “Danish” database, provides sector- and size-specific WH estimates derived from national energy statistics and process-level analyses through a top-down, process-based mapping framework [42].

For each industrial sector and employee-size class, energy consumption is allocated to typical industrial processes, and the corresponding recoverable WH is estimated through literature-based recovery assumptions and temperature-specific characterisation. Within this original Danish industrial mapping framework, most industrial WH is found at relatively low temperatures, with the large majority reported below 100 °C [42].

In the subsequent Heat Plan Denmark 2021 framework [13] made accessible through the Danish Energy Maps (EnergyMAPS) tool [43], industrial WH is organised into three temperature levels, namely high-temperature (>80 °C), medium-temperature (60–80 °C), and low-temperature (<60 °C) [13]. These classes are not intended as a generic thermodynamic classification of industrial waste heat, but rather as a DH-oriented screening framework linked to the suitability of excess heat for integration into different generations of DH. In particular, sources above 80 °C are assumed to be directly utilisable in 3GDH, whereas in 4GDH direct utilisation is extended to sources above 60 °C because of the lower network supply temperature. Consequently, the 60–80 °C range is especially relevant in distinguishing 3GDH from 4GDH, since it generally requires upgrading in

3GDH but may be directly exploited in 4GDH, while sources below 60 °C typically require temperature boosting by heat pumps [13]. Accordingly, these thresholds should be interpreted as planning-oriented integration criteria rather than intrinsic source categories, and the effective recoverability of each WH source remains dependent on site-specific conditions and network operating temperatures.

This DH-oriented classification is consistent with recent Danish work assessing excess-heat sources for current and future baseload DH supply in the context of both 3GDH and 4GDH planning [11]. Employee-size classes adopted in this study range from 20 to more than 1000 employees, as reported in Table 1. Although the number of employees is not an ideal proxy for industrial energy use, it represents the only consistently available metric across large databases; in the absence of production volumes or process-specific activity data, it provides a practical and scalable basis for estimating WH potential. The annual WH potential is provided for each temperature level within each sector-size combination. This database therefore enables a scalable, transparent and internally consistent first-stage screening of WH potential across case studies and is publicly accessible through the Danish Energy Maps [43].

In addition to the Danish method, this study also employs a second reference dataset to assess and compare the uncertainty inherent in WH mapping sources. Specifically, the “Austrian”, developed by the Austrian Institute of Technology, i.e., MEMPHIS database [44], is applied as an alternative benchmark. This approach follows a statistical bottom-up methodology, starting from activity-specific energy consumption data for selected industrial processes and deriving corresponding WH estimates.

Table 1: Employees’ classes for the Danish waste heat database.

Employees class index	Minimum n. employees	Maximum n. employees
5	20	49
6	50	99
7	100	199
8	200	499
9	500	999
10	1000	+∞

2.2.2 Method

The estimation of industrial WH potential within the proposed mapping framework is based on the Danish reference database, which is queried using facility-specific input data and refined through a custom interpolation procedure developed by Eurac Research. Rather than being implemented as discrete procedural steps, the methodology operates as a continuous workflow that combines database lookup, mathematical transformation and temporal disaggregation to obtain detailed WH estimates for each facility in the area of analysis.

For each industrial site, an initial annual WH value is extracted from the Danish dataset through a function that depends on three parameters: the industrial sector code s (3-digit NACE), the employee class index i_e and the temperature level index i_T . This can be expressed as:

$$Q_{(y,s)}^{WH} = Q(s, i_e, i_T),$$

The Danish database returns the corresponding annual WH potential at the three temperature levels, low, medium and high, forming the vector:

$$Q_{(y,s)}^{WH} = [Q_{(y,s,T_L)}^{WH}, Q_{(y,s,T_M)}^{WH}, Q_{(y,s,T_H)}^{WH}].$$

In this formulation, all facilities sharing the same activity code and employee-size bracket receive identical WH potential. While this ensures consistency and comparability across large datasets, it introduces a stepwise structure that may limit accuracy at the individual facility scale, especially for firms located near class boundaries.

To overcome this limitation and allow the WH potential to vary continuously with the exact number of employees, a piecewise linear interpolation model was applied to the Danish dataset. The resulting function replaces the employee class index with the actual workforce size n_e :

$$\widehat{Q}_{(y,s)}^{WH} = Q(s, n_e, i_T).$$

The interpolation intervals are defined using the algebraic average of each employee class:

$$\bar{i}_e = \frac{i_e^{min} + i_e^{max}}{2},$$

which establishes the domain for each piecewise segment $\Delta i_e : n_e \in [\bar{i}_e, \bar{i}_e + 1]$. To ensure full coverage of very small facilities, an additional lower interval is

added for sites with fewer than 35 employees (Δi_4), while the upper interval (Δi_9) is handled through extrapolation because its upper bound is unbounded.

For each industrial sector and temperature level, a piecewise linear regression relationship is defined over each interval through:

$$lr_{s,i_T,\bar{\Delta}i_e}(n_e):$$

$$\widehat{Q}_{(y,s,i_T,\bar{i}_e)}^{WH}(n_e) = \widehat{Q}_{(y,s,i_T,\bar{i}_e)}^{WH} + \frac{\widehat{Q}_{(y,s,i_T,\bar{i}_{e+1})}^{WH} - \widehat{Q}_{(y,s,i_T,\bar{i}_e)}^{WH}}{\bar{i}_{e+1} - \bar{i}_e} (n_e - \bar{i}_e).$$

with specific formulations applied to the lowest and highest intervals. For Δi_4 , WH is assumed to be zero for zero employees, producing:

$$\widehat{Q}^{WH}(n_e) = \frac{\widehat{Q}_{(y,s,i_T,\bar{i}_5)}^{WH}}{\bar{i}_5} n_e, n_e \in [0, 35].$$

For Δi_9 , the slope of the previous interval is extended to estimate WH values beyond \bar{i}_9 . Any missing values in the original Danish dataset are filled through linear interpolation between adjacent employee classes to ensure dataset continuity. These profiles are derived from sector-specific activity patterns, reflecting process phases, standard working shifts, seasonal or daily variations and scheduled downtime for holidays or maintenance, consistent with industrial load-profile characterisation found in the literature. After computing the annual WH potential $\widehat{Q}_{(y,s,i_T,n_e)}^{WH}$, an hourly WH time series is generated using dimensionless temporal profiles $\alpha_{(h,s,i_T)}$, which represent typical operational behaviour of each industrial sector and temperature level.

The hourly WH potential is therefore obtained as:

$$\widehat{Q}_{(h,s,i_T,n_e)}^{WH} = \widehat{Q}_{(y,s,i_T,n_e)}^{WH} \alpha_{(h,s,i_T)},$$

where $\sum_{h=1}^{8760} \alpha_{(h,s,i_T)} = 1$. These profiles may originate from literature or be generated based on representative industrial activity patterns.

Although the Danish database is used here as the reference source, the proposed methodology is fully generalisable and can be applied to any alternative WH dataset that provides a link between industrial processes, activity categories and facility size.

2.2.3 Outputs

The first output consists of mapping all industrial sources within the area of interest that can potentially generate WH, along with estimating their annual thermal potential in MWh/year across the three temperature levels. A filtering step can then be applied to retain only the most relevant facilities, based on customizable criteria designed to prioritise high-potential sources. The second output converts the annual WH potential into an hourly profile using default hourly profiles representative of typical operating patterns for each industrial sector.

2.3 Tertiary Waste Heat

2.3.1 Inputs

The identification of potential tertiary waste heat sources is based on a semi-automated GIS-driven mapping process that collects and preprocesses information on relevant urban facilities. This procedure requires two complementary types of data: a detailed geospatial dataset describing the location, geometry and activity type of tertiary buildings and reference information from literature and technical studies providing WH coefficients for the corresponding activity categories.

The first input consists of a geospatial inventory of tertiary facilities within the area of interest, retrieved through the Eurac mapping plugin [41] developed in the framework of the LIFE4HeatRecovery project [45]. The tool extracts data from OpenStreetMap (OSM) and Google Services, which provide geometric features and descriptive tags suitable for identifying activities of interest, such as supermarkets, shopping centres, hospitals, swimming pools and ice rinks. These categories are representative of tertiary uses characterised by high internal heat gains or by continuous operation of cooling and refrigeration systems and are therefore promising WH sources.

The raw OSM and Google datasets must be pre-processed to ensure consistency, completeness and suitability for WH estimation. The preprocessing workflow, implemented within GIS, includes removing duplicated features, standardising activity classifications, retaining only relevant and complete entries and reorganising the information into a harmonised structure. The plugin extracts three essential attributes for each facility: location, type of activity and geometric size. Additional metadata, such as company names or OSM identifiers, are transferred from larger geometries (e.g., building polygons or relations) to smaller ones (typically points), ensuring that all relevant information is preserved in the most elementary spatial entity.

Due to the collaborative and non-standardised nature of OSM and Google Maps, inconsistencies may arise from heterogeneous mapping practices. Facilities may appear in different geometric forms (points, ways, or relations), or be duplicated across datasets. The preprocessing routines, therefore, consolidate metadata, eliminate redundant entries and ensure a one-to-one correspondence between each WH source and its final mapped representation.

The resulting harmonised dataset associates each tertiary facility with the following core attributes:

- company name (when available) or unique ID,
- location in the form of addresses or geographic coordinates,
- footprint area [m²],
- number of floors,
- activity classification.

When the number of building levels is not explicitly available, it is estimated using a semi-automatic procedure in GIS, based on the ratio between building height, derived from Digital Surface Models (DSM) and standard floor height assumptions. This enables calculation of the gross floor area, which is the key parameter for estimating WH potential in tertiary buildings.

Finally, an expert validation phase is performed to check the completeness, coherence and plausibility of the identified WH sources before WH calculations are carried out. This ensures high data quality and minimises errors stemming from crowd-sourced mapping inputs.

The second essential input consists of reference values for WH potential associated with each tertiary activity type. These coefficients, derived from previous research projects (e.g., LIFE4HeatRecovery), energy studies and technical literature, provide estimates of recoverable WH per square metre of gross floor area and enable subsequent calculation of annual and hourly WH potentials. In contrast to the industrial sector, where employee count is often the only consistently available proxy for sizing, tertiary WH can more reliably be linked to building geometry, as service-oriented facilities are typically dimensioned according to their functional use and occupancy, making gross floor area a meaningful indicator of their WH potential. The specific sources and values adopted in this work are detailed in Section 2.3.2.

2.3.2 Method

Unlike industrial WH, where recoverable heat is characterised by multiple temperature levels and linked to sector-specific process data and employee classes,

tertiary WH is assumed to be entirely available at low temperature (~25 °C). As a consequence, recovery from these facilities requires thermal upgrading, typically via heat pumps, before injection into a DH. The estimation methodology for tertiary WH is therefore based on empirical formulations that use geometric attributes (e.g., footprint and gross floor area) and activity classifications, rather than detailed operational data.

In this framework, WH potential is quantified by applying a set of activity-specific coefficients and rules to the geometries and metadata extracted through the mapping procedure described in the previous section. The amount of tertiary WH is generally correlated to the gross floor area of each facility or, in some cases, to fixed representative values derived from reference case studies. The following paragraphs describe the estimation procedures applied to each of the tertiary activity categories considered.

2.3.2.1 Hospitals and clinics

For hospitals and clinics, the annual WH potential is estimated as:

$$\widehat{Q}_{(y,s=hosp)}^{WH} = A n_f q^{WH} [kWh y^{-1}],$$

where:

- A is the footprint area [m²];
- n_f is the number of floors;
- q^{WH} represents the specific thermal energy source per year per unit area [kWh m⁻² y⁻¹].

The coefficient $q^{WH} = 18 kWh m^{-2} y^{-1}$ is derived from a statistical analysis of hospitals in the United States reporting an average electricity use intensity of 600 kWh m⁻² y⁻¹, of which 3% corresponds to refrigeration [45].

2.3.2.2 Ice rinks

For ice rinks, WH potential is based on evidence from a case study in Munich [46]. After deducting the internal heating demand from the condenser recovery, the net WH available is approximately 70 MWh per month, corresponding to:

$$\widehat{Q}_{(y,s=icerinks)}^{WH} = 840 MWh y^{-1}$$

under year-round operation. Because ice rinks have standardised surface dimensions, no geometric scaling is applied. If the facility operates only during part of the year, this value should be scaled according to the actual operating period.

2.3.2.3 Malls and supermarkets

For retail buildings, i.e., supermarkets and shopping malls [47], WH potential is linked to the gross floor area and to the fraction of space dedicated to food refrigeration:

$$\widehat{Q}_{(y,s=retail)}^{WH} = w A n_f \alpha_{food} \alpha_{fridge} COP [kWh y^{-1}],$$

where:

- w = specific electricity consumption associated with retail refrigeration uses [kWh m⁻² y⁻¹],
- A = footprint area [m²],
- n_f = number of floors,
- α_{food} = share of area dedicated to food sales,
- α_{fridge} = share of food area equipped with refrigeration,
- COP = coefficient of performance.

Default values are: COP = 3; $\alpha_{fridge} = 0.5$; $\alpha_{food} = 0.2$ for malls and $\alpha_{food} = 1$ for supermarkets.

As in the industrial methodology, annual WH potential is converted into hourly time series through dimensionless sector-specific profiles:

$$\widehat{Q}_{(h,s)}^{WH} = \widehat{Q}_{(y,s)}^{WH} \alpha_{(h,s)},$$

where the hourly profile satisfies:

$$\sum_{h=1}^{8760} \alpha_{(h,s)} = 1.$$

These curves are defined as representative dimensionless hourly profiles based on the typical operating patterns of the corresponding activities and assigned through expert judgment for screening-level purposes. The QGIS plugin is also able to detect activities like swimming pools and laundries. After identifying such activities through geo-tagging, geometric and technical parameters are combined to filter out non-relevant cases (e.g., private swimming pools and small laundries). WH estimates taken from literature, swimming pools [48] and laundries [45], are then used for a general assessment. It is however worth stressing that heat recovery from these activities is highly challenging, due to the small WH volumes and the time profiles (typically not matching the heating demand, especially for swimming pools), which make it hardly economically feasible.

It is important to note that the coefficients adopted for each tertiary category represent generic reference values; their applicability may vary across individual facilities depending on specific operating conditions, technologies and usage patterns. As such, these values should be

interpreted as indicative and can be adjusted on a case-by-case basis whenever more detailed local information is available. Additional categories of waste heat, such as data centres or other commercial facilities, can be integrated into the methodology when suitable activity-specific coefficients and sufficiently reliable open datasets become available. At present, their inclusion is limited by the scarce public availability of detailed information, as such data are often sensitive.

2.3.3 Outputs

In this case as well, the first output provides a spatial inventory of tertiary facilities with potential WH availability, for which the annual recoverable energy (MWh y^{-1}) is estimated using gross floor area and activity-specific coefficients. All tertiary sources are treated as low-temperature WH sources. A subsequent filtering step enables users to prioritise the most relevant facilities by applying customised thresholds, thereby focusing on high-yield opportunities. These thresholds were selected on techno-economic grounds, as sources located too far from the network become excessively costly to connect, while sources with very small annual WH potentials are generally not attractive because the costs of connection and heat recovery are too high compared to the recoverable energy. The second output translates each facility's annual WH estimate into an hourly profile, using representative temporal profiles that capture the typical operating behaviour of each tertiary activity category.

2.4 Energy system analysis

The DH system is analysed through an aggregated, hourly-resolved model developed in Python to assess the impact of integrating new heat sources, particularly waste heat, on the overall operation of the network. The model represents the system using a single demand node and a single production node, linked through hourly energy balances. This modelling approach builds upon previously validated formulations for aggregated DH simulations [49] and is specifically intended for the planning phase and for early-stage system assessment. In this context, it is particularly suitable for evaluating the integration of new energy resources, estimating their potential contribution to heat supply, and defining alternative decarbonisation scenarios before moving to detailed design and implementation stages.

The main inputs include the aggregated hourly heat demand of the users, supply and return network

temperatures, ambient air temperature and basic parameters of the heat production units. Thermal network losses are estimated as a function of the average network temperature, the ground temperature, derived from pipe burial depth and ambient temperature and the network's overall heat transfer coefficient, which is calibrated for the specific case study.

At each time step, the total heat demand, given by user demand plus network losses, is met through a combination of heat production units and thermal storages. Heat sources are grouped into primary and auxiliary units, following a hierarchical dispatch approach: primary sources (e.g., low-carbon or renewable sources) are prioritised, followed by storage charging/discharging depending on system conditions and finally auxiliary units are activated if needed. The actual thermal output of each unit is determined by its available capacity, modulation limits and the residual demand to be covered. Thermal storages operate within their charging/discharging power limits and maximum capacity. In this example, storage is represented as short-term thermal storage for day-night balancing.

Waste heat sources are modelled as a primary source and characterised by two hourly profiles: available thermal power and source temperature. Based on its temperature level, WH can be integrated either directly into the network, when the available temperature exceeds the supply temperature of the network, or via a heat pump when temperature upgrading is required. Accordingly, the effective integration pathway is assessed based on the actual WH source temperature and the operating temperature level of the target DH network, thus enabling a consistent evaluation of low and medium-temperature WH integration under different network conditions. For each WH sub-category (e.g., factory, hospital, supermarket, etc), the hourly availability profile is derived from the estimated annual WH potential and representative sector-specific temporal patterns defined in the mapping procedure.

This aggregated formulation enables a robust simulation of the system-level effects of WH integration, including the share of demand covered by WH, the resulting reduction in fossil-fuel-based heat generation and the interaction with thermal storages. Despite its simplified structure, the model provides a reliable basis for evaluating the operational and strategic implications of WH integration in future decarbonisation and network-modernisation scenarios. At the same time, as an aggregated single-node formulation intended for the planning phase and early-stage assessment,

it does not explicitly represent detailed spatially resolved production and distribution aspects, which should be addressed separately in subsequent design and implementation phases through dedicated network analyses.

3. Application

Milan represents an ideal case study for demonstrating the proposed methodology, owing to its metropolitan scale, diverse mix of industrial and tertiary activities with significant WH potential and the presence of established DH networks operated by A2A Calore e Servizi. Located in northern Italy, within the Lombardy region, the city covers an area of 181.7 km², has a population of approximately 1.37 million inhabitants and is characterised by a humid subtropical climate with hot summers and cold winters, conditions that lead to a pronounced seasonal heating and cooling demand. The analysis first considers the entire municipal territory to assess the WH potential from all eligible industrial and tertiary activities and subsequently focuses on the Milan West DH network, one of the three main DH networks in the city, together with the Milan East and Milan North networks, to evaluate how this potential can be practically integrated into a DH system and to assess the resulting implications.

Using 2023 as the reference year, the Milan West DH network represents one of the largest thermal infrastructures in Italy. The system comprises approximately 123 km of distribution pipelines and an installed thermal capacity of more than 300 MW (see Figure 1). The network can therefore be regarded as a conventional 3GDH system, given its centralised supply architecture, integration within A2A Calore e Servizi's Milan DH system, relatively high operating temperatures and generation mix dominated by waste-to-energy and gas-fired units. Its generation mix is dominated by the Waste-To-Energy (W2E) facility Silla 2, located in the north-western sector of the city, which alone provides a nominal thermal capacity of 144 MW. Additional supply is ensured by the Famagosta natural-gas boiler plant (96 MW) and the Selinunte methane-gas boiler (36 MW), complemented by two methane-gas units at Giambellino and Bensi (18 MW and 8 MW, respectively). In 2023, total heat production reached 438.8 GWh, of which W2E accounted for 383.9 GWh (87.5%), followed by the Famagosta with 47.2 GWh (10.8%) and the Selinunte with 7.7 GWh (1.7%). When classified by fuel type, W2E represented the dominant source (383.9 GWh), while natural gas and methane contributions were significantly lower (47.2 and 7.7 GWh, respectively). In this study, W2E is partly considered renewable. For the purpose of this study,

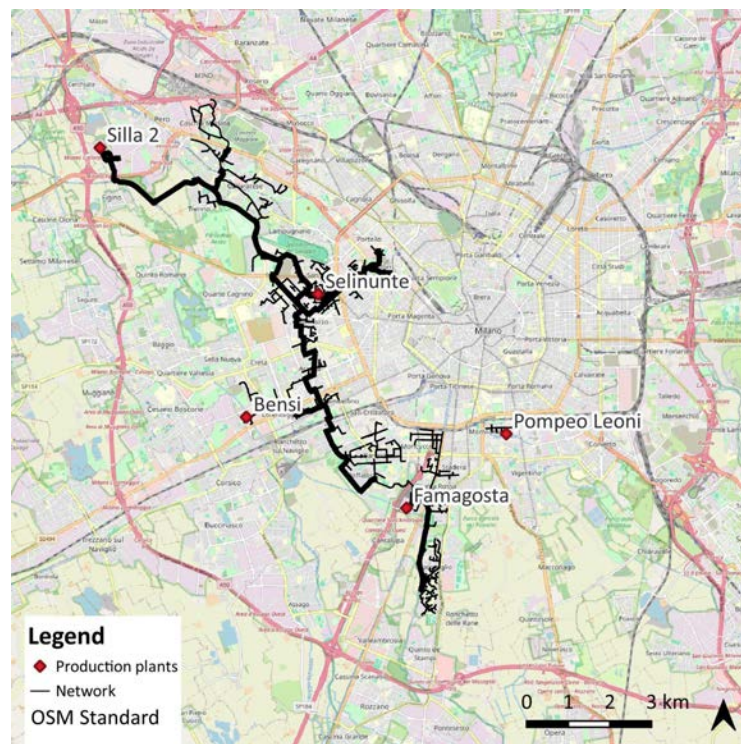


Figure 1: Layout of the Milan West district heating along with the production sites: Silla 2, Selinunte, Bensi and Famagosta.

and consistently with its demonstrative objective of assessing the WH mapping methodology and the implications of WH integration into DH, it is assumed that only 30% of Silla 2's output is accounted for as RES in the model. This results in an overall renewable share of 26.2% in 2023, the remaining heat supply derives from non-renewable fuels (natural gas and methane) and from the assumed non-renewable fraction of W2E, with no WH present in the generation mix.

In this context, there is a need to align the system with EED by increasing the share of renewable energy and/or waste heat, especially in light of the substantial demand growth planned for the coming years, making it strategically relevant to exploit the numerous WH opportunities available across the metropolitan area as well as to integrate new RES and high-efficiency combined heat and power (CHP) solutions.

4. Results

This section presents the outcomes of the proposed WH mapping methodology on the case of Milan city in Section 4.1, including the analysis of the WH integration in Milan West DH in Section 4.2 and the comparison between the Danish and Austrian WH datasets in Section 4.3.

4.1 Mapping WH in Milan

The city of Milan represents an effective test case for demonstrating the applicability and robustness of the proposed WH mapping methodology, thanks to its large urban scale, the coexistence of diverse industrial and tertiary activities and the presence of established 3GDH networks. The WH mapping performed for the entire municipal area identified a total of 2,180 sources, of which 642 belong to the tertiary sector and 1,538 to the industrial sector. Figure 2 shows the spatial distribution of these sources across the municipality, classified according to their estimated annual WH potential. Detailed information for each individual activity, including the estimated WH potential across the three temperature levels, is available in the HeatMineDH Explorer [50].

Figure 3 summarises the composition of the mapped WH sources, distinguishing sectoral distribution and temperature levels. The outer ring shows that industrial sources account for approximately two-thirds of the identified sources, while the inner ring highlights that most of the estimated WH potential is available at low temperature (74%), while 13% each available at medium and high temperature.

Figure 4 provides an overview of the WH potential by temperature level and size class. Low-temperature sources

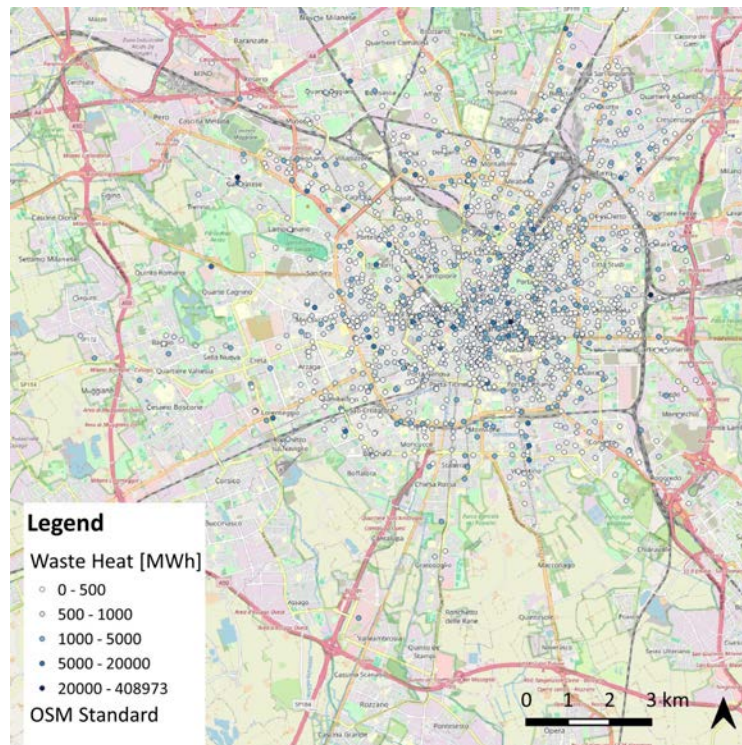


Figure 2: Map of the resulting waste heat potential obtained from the proposed methodology for the city of Milan.

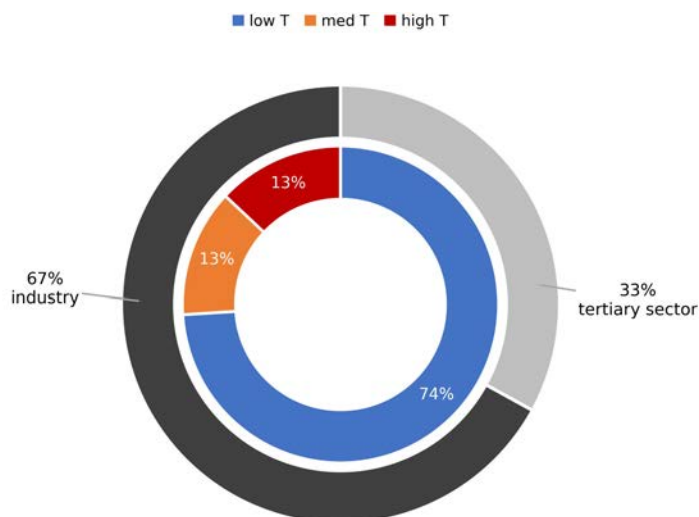


Figure 3: Distribution of the identified WH sources in Milan by sector (outer ring) and by temperature level (inner ring).

exhibit the widest distribution across all potential classes, with nearly half of the sources below 100 MWh y⁻¹ and a significant share between 101 and 1,000 MWh y⁻¹. Medium- and high-temperature sources are instead predominantly associated with small potentials (< 100 MWh y⁻¹), with only a marginal fraction exceeding 1,000 MWh y⁻¹.

The distribution of WH potential across activity types reflects the economic structure of Milan, where

a dense tertiary sector coexists with several specialised industrial clusters. The highest WH densities (i.e., WH per facility) are found in pharmaceutical and chemical industries, where medium-temperature WH originates primarily from evaporation and reaction processes, complemented by low-temperature recovery from refrigeration systems. Significant contributions also emerge from the food and beverage

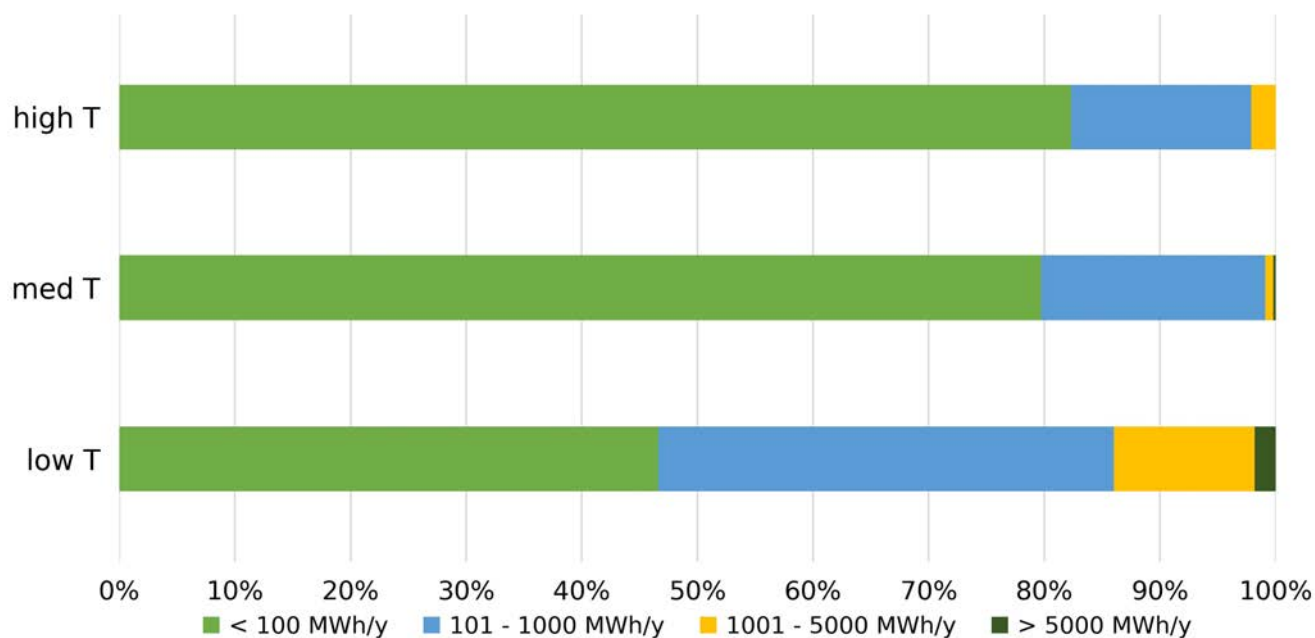


Figure 4: Distribution of WH sources in Milan by temperature level (low, medium, high) and potential class.

sector, especially dairies and cheese production, which combine heat from thermal treatment with substantial cooling demands.

High-temperature WH is mainly associated with paper, wood and basic metal manufacturing, where

combustion, drying, or smelting processes generate substantial excess heat. In contrast, the retail and wholesale sectors contribute large volumes of low-temperature WH, driven by widespread refrigeration units distributed across supermarkets and storage facilities. These

Table 2: Annual WH potential by activity type in the municipality of Milan, including the number of units, WH potential by temperature level (low, medium, high), total WH potential and average WH per activity type.

Activity division description	N. of units	Low [T GWh]	Med [T GWh]	High [T GWh]	Tot [GWh]	Avg [GWh]
Manufacture of basic pharmaceutical products and pharmaceutical preparations	39	179.5	14.5	14.9	208.9	5.4
Manufacture of beverages	11	31.9	6.7	9.3	48.0	4.4
Manufacture of chemicals and chemical products	104	149.4	92.7	44.8	286.9	2.8
Manufacture of food products	136	268.7	27.7	69.8	366.2	2.7
Other mining and quarrying	5	9.1	0.3	2.0	11.4	2.3
Manufacture of basic metals	49	3.4	50.0	11.1	64.4	1.3
Manufacture of paper and paper products	23	1.4	3.0	24.9	29.3	1.3
Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials	28	5.0	3.8	23.6	32.4	1.2
Retail trade, except of motor vehicles and motorcycles	255	290.1	0.0	0.0	290.1	1.1
Human health activities	111	100.5	0.0	0.0	100.5	0.9
Other personal service activities	154	130.6	0.0	0.0	130.6	0.8
Wholesale trade, except of motor vehicles and motorcycles	124	85.1	0.0	0.0	85.1	0.7
Manufacture of rubber and plastic products	104	37.0	16.6	1.4	54.9	0.5
Manufacture of other non-metallic mineral products	19	0.8	1.9	6.0	8.7	0.5
Manufacture of machinery and equipment n.e.c.	176	43.5	12.3	9.2	65.0	0.4
Manufacture of furniture	36	6.3	1.3	2.9	10.4	0.3
Manufacture of electrical equipment	66	7.9	4.0	2.0	13.9	0.2
Manufacture of tobacco products	1	0.1	0.0	0.1	0.2	0.2
Manufacture of motor vehicles, trailers and semi-trailers	19	0.9	1.3	1.2	3.3	0.2
Manufacture of computer, electronic and optical products	68	5.7	1.9	1.5	9.1	0.1
Manufacture of textiles	51	1.2	2.6	3.0	6.7	0.1
Printing and reproduction of recorded media	67	5.6	0.7	0.6	7.0	0.1
Manufacture of other transport equipment	15	0.9	0.3	0.1	1.3	0.1
Manufacture of fabricated metal products, except machinery and equipment	273	0.6	7.7	4.5	12.8	<0.1
Other manufacturing	29	0.4	0.5	0.3	1.2	<0.1
Repair and installation of machinery and equipment	105	0.8	0.9	1.2	2.9	<0.1
Manufacture of leather and related products	25	0.1	0.3	0.4	0.7	<0.1
Manufacture of wearing apparel	85	0.0	0.1	0.2	0.4	<0.1
Food and beverage service activities	2	0.0	0.0	0.0	0.0	<0.1

Table 3: Waste Heat potential selected for integration into the Milan West DH.

	Low Temperature [GWh]	Medium Temperature [GWh]	High Temperature [GWh]	Total [GWh]
Urban WH	81.4	0.0	0.0	81.4
Industrial WH	17.0	1.4	1.4	19.8
Total	98.4	1.4	1.4	101.2

findings confirm that, in Milan, the most relevant WH sources span both energy-intensive industrial processes at medium- and high-temperature and widespread tertiary refrigeration loads at low temperature, offering complementary integration opportunities for DH systems. At the same time, the predominance of low-temperature WH highlights the strategic relevance of network temperature reduction for enabling broader and more efficient integration of WH via heat pumps.

4.2 WH integration in the Milan West DH

The Milan West DH represents a relevant case for evaluating how spatially resolved WH mapping can inform decarbonisation strategies in existing 3GDH networks. The system relies predominantly on the Silla 2 W2E plant, which, under the modelling assumption adopted in this study, results in an overall RES/WH contribution of 26.2% in 2023. To comply with forthcoming EED requirements and accommodate the projected growth in heat demand, the operator aims to expand the supply portfolio by integrating external WH sources supported by heat pumps and high-efficiency CHPs. The city-wide WH mapping shown in Figure 2 constitutes the basis for identifying the most relevant opportunities for the Milan West network.

Starting from the complete set of industrial and tertiary WH sources identified across Milan, a selection and validation process was carried out to determine which facilities could realistically be connected to the Milan West DH. Two criteria were applied: (i) a distance of less than 1 km from the existing network and (ii) an annual WH potential exceeding 1 GWh y^{-1} . This screening procedure ensures that only sources with a sufficiently large recoverable potential and with connection requirements that do not entail excessively long and costly pipelines are retained, thus focusing the analysis on economically viable WH integration opportunities. The final technical WH potential suitable for integration into the Milan West DH amounts to approximately 100 GWh y^{-1} , with over 97% available at low temperature. Given the conventional 3GDH configuration of the Milan West network, this composition

indicates that most of the technically accessible WH, with low- and medium-temperature sources accounting for about 99% of the selected technical potential, requires temperature upgrading through heat pumps before being integrated into the system. Table 3 summarises the contributions by sector and temperature level, while Figure 5 illustrates the spatial resolution of those sources.

On the industrial side, the screening process identified four facilities, all belonging to the Manufacture of pharmaceutical preparations. These plants collectively provide 19.8 GWh y^{-1} , including the only contributions at medium and high temperature among the selected sources (1.4 GWh y^{-1} each), while the remaining 17.0 GWh y^{-1} are available at low temperature. This limited but valuable industrial segment reflects both the spatial constraints of the Milan area and the predominance of tertiary sources in the municipality. In contrast, the urban WH component amounts to 81.4 GWh y^{-1} and derives from a more diverse set of tertiary categories. The largest contributions stem from supermarkets and shopping malls, whose refrigeration systems generate a continuous low-temperature excess heat stream.

After defining the feasible WH sources, the annual values for each activity type are converted into hourly profiles, enabling the energy analysis to assess their impact on the operation of the Milan West DH. Figure 6 shows the reference status of the network, including the monthly heat production and the annual supply shares. The reference configuration corresponds to a total annual heat supply of 438.8 GWh. W2E from the Silla 2 plant (144 MW) fully covers the demand during the non-heating season, while in winter the residual load is supplied by the gas-fired boilers, specifically Famagosta (96 MW) and Selinunte (36 MW) in this order of priority. The annual breakdown confirms the strong dependence on non-renewable sources and no contribution from waste heat. This configuration constitutes the baseline for assessing WH integration in the following analysis.

A first scenario without demand growth was analysed by integrating the available WH into the system through

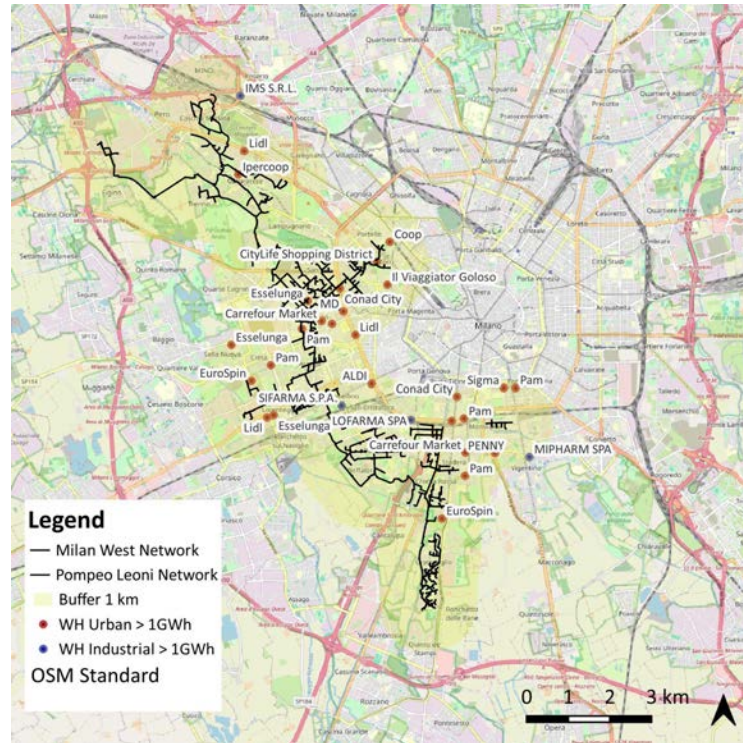


Figure 5: Map of the selected waste heat potential for integration into the Milan West DH.

heat pumps. With the dispatch order kept unchanged, Silla 2 W2E as the primary source, followed by WH and finally the gas boilers at Famagosta and Selinunte, the model produces the results shown in Figure 7. WH is primarily exploited during the winter months, bringing the WH share to 5.4% and reducing the non-renewable share to 68.3%. However, only about 13% of the selected technical WH potential could be effectively recovered under the simulated operating conditions; after temperature upgrading through heat pumps, this yielded 23.9 GWh of heat

supplied to the DH. This limited utilisation is mainly due to the dominant role of W2E, which retains priority in the dispatch order and therefore reduces the operational space available for WH integration. This choice also reflects an operational constraint of the network operator, since W2E is an already available, integrated and comparatively cost-effective source that must be prioritised in order to avoid wasting a resource that is already present in the system. Moreover, the selected WH potential is estimated on an annual basis, whereas in practice its actual use is

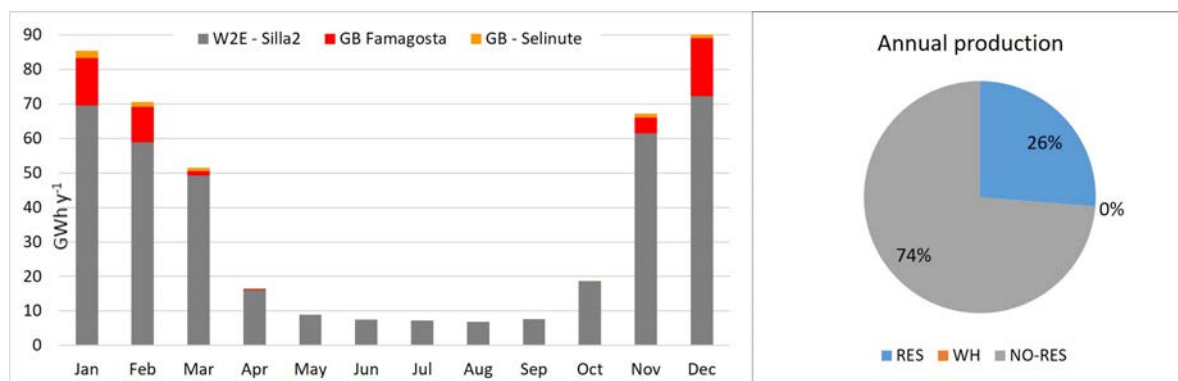


Figure 6: Reference status of the Milan West DH in 2023, including the monthly distribution of heat production (left panel) and the annual production by source type (right panel).

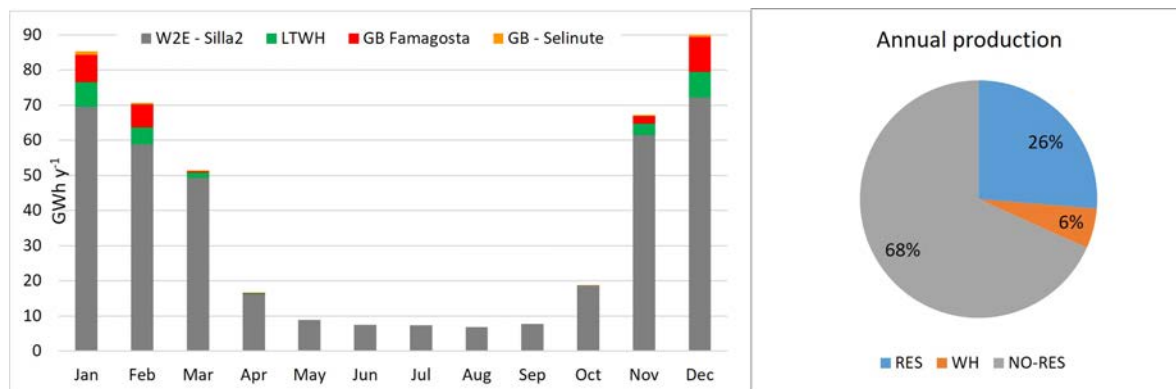


Figure 7: Scenario with WH integration and same heating demand of the Milan West DH, including the monthly distribution of heat production (left panel) and the annual production by source type (right panel).

constrained by hourly matching between source availability and network demand; a substantial share cannot be exploited, particularly during the non-heating period, when the thermal load is already fully covered by W2E.

Finally, a scenario with a 50% increase in heat demand was analysed and the results are shown in Figure 8. With the same dispatch priorities maintained, W2E from Silla 2 continues to supply most of the heat (74%), followed by WH recovered through heat pumps (11%) and gas boilers at Famagosta and Selinunte (15%). In this configuration, WH accounts for about 11% of the total heat supply, while 66.8% remains non-renewable due to the limited RES share of W2E (30%) and the contribution of gas boilers.

Despite the higher demand, only a limited portion of 40% of the available selected WH potential is effectively utilised. W2E still covers almost the entire non-heating season and during winter the recoverable WH cannot always be fully injected because of the need for hourly matching between supply and demand. The residual load

is therefore met by gas boilers. This indicates that increasing heat demand alone is not sufficient to maximise WH uptake if dispatch priorities remain unchanged and system flexibility is limited.

These results illustrate that, even when technically available, WH cannot be fully exploited in a DH and a detailed hourly energy-system analysis is crucial to assess its operational feasibility. They also highlight that maximising WH utilisation requires assigning higher dispatch priority and integrating WH within a more flexible system architecture, where thermal energy storage (TES) can play a key role in increasing the effective absorption of low-temperature excess heat. This is particularly relevant for conventional 3GDH systems such as Milan West, where the predominance of low-temperature WH makes heat pumps and operational flexibility central to effective integration.

The predominance of low-temperature waste heat among the sources identified for Milan also has broader systemic implications. First, it confirms that heat pumps are

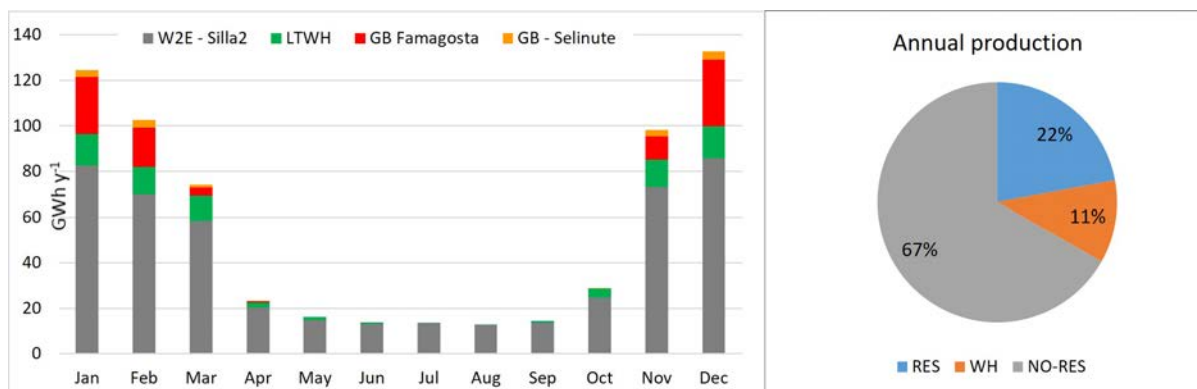


Figure 8: Scenario with WH integration and 50% heating demand increase of the Milan West DH, including the monthly distribution of heat production (left panel) and the annual production by source type (right panel).

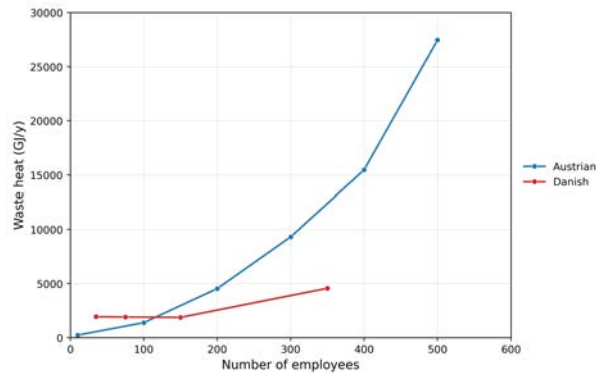


Figure 9: Comparison of WH estimates for bakeries (NACE 10.70) from the Danish and Austrian datasets as a function of company size.

a key enabling technology for the integration of urban WH into DH, since most of the technically accessible sources cannot be directly injected into the network and therefore require temperature upgrading. Second, it highlights the close link between urban waste heat recovery and the broader electrification of the heating sector, as many low-temperature excess-heat streams can still provide favourable operating conditions for heat pumps compared with ambient sources. At the same time, the limited contribution of medium- and high-temperature waste heat reflects a structural feature of the urban context: higher-temperature industrial excess heat is more often internally recovered within industrial processes, while high-temperature activities are typically less common in dense urban areas and more frequently concentrated in dedicated industrial zones. As a result, urban WH integration strategies are likely to rely primarily on the combination of low-temperature source recovery, heat pumps and flexible DH operation. In this perspective, the ongoing transition from conventional 3GDH configurations towards lower-temperature DH can further support the efficient integration of low-temperature waste heat, by reducing the required temperature lift and therefore improving the overall performance of heat-pump-based recovery solutions.

4.3 Comparison among waste heat databases

The WH mapping methodology presented in this work provides indicative estimates of the recoverable heat potential and is therefore suited for preliminary screening and strategic assessment. Before progressing to detailed design or investment phases, each opportunity must be verified on a case-by-case basis, as the actual WH availability depends on specific parameters, such as building geometry, type of activity, operational schedules and process characteristics, that cannot be fully captured through an automatic methodology.

A further source of uncertainty lies in the reference database adopted for the estimation. In this study, the Danish dataset was used due to its broad sectoral coverage and structured employee-based methodology, yet alternative datasets exist. The Austrian dataset, for example, follows a bottom-up approach based on process-specific energy statistics. As datasets often differ in both industrial coverage and underlying calculation approach, they may lead to significantly different WH estimates. For instance, Figure 9 compares the two datasets for bakeries (NACE 10.70): while both indicate an increasing WH potential with company size, the Austrian values rise much more steeply, reflecting the inclusion of detailed thermal process steps, whereas the Danish method provides more conservative estimates anchored to average energy intensities. This comparison therefore highlights that the choice of reference dataset can have a substantial influence on the estimated WH potential and should be regarded as a relevant source of methodological uncertainty.

These discrepancies highlight that WH mapping should be interpreted as an initial territorial screening tool, providing an indication of where WH recovery may be promising for future DH decarbonisation. However, given the methodological variability and the intrinsic uncertainty in activity-specific data, detailed site-specific verification remains essential to accurately quantify the recoverable WH and assess its real feasibility for integration. In this respect, future applications of the methodology should be complemented by site-specific feasibility assessments and, where possible, validation against measured WH streams or detailed local energy data. Nevertheless, the mapping methodology remains a valuable instrument for obtaining an overall picture of the WH potential and for guiding future planning actions and detailed feasibility studies.

5. Conclusion

This study aimed to make WH potential data readily available for the development of DH modernisation scenarios. The proposed methodology provides a structured workflow to retrieve, estimate and characterise potential WH sources within urban contexts, offering indicative annual energy potentials, temperature levels and hourly availability profiles according to the type of activity.

The results demonstrate a robust and scalable methodology capable of delivering high-resolution spatial and temporal datasets that serve as valuable inputs for modelling and decision-making processes in DH decarbonisation strategies. The developed methodology integrates open geographic data, statistical information and literature-based coefficients, enabling the identification and quantification of both industrial and tertiary WH sources with a high degree of consistency.

The Milan case study illustrates three main outcomes: the applicability of the methodology in an urban context, demonstration of how WH integration can inform energy scenario development in decarbonisation planning and assessment of the uncertainty of WH potential estimation by comparing results derived from Danish and Austrian WH reference datasets. The results also highlight that the predominance of low-temperature WH makes heat pumps and, more broadly, the transition

towards lower-temperature DH particularly relevant for expanding the effective integration of urban WH.

Although comprehensive, the current framework still lacks certain source categories, such as data centres, which could be integrated in future developments by combining the existing workflow with information from emerging specialised atlases, e.g., [51]. Furthermore, future refinements should address the share of internal WH reuse within each activity type. The methodology is intended as a screening and planning-support tool to identify, map and characterise potential WH sources at territorial scale, thereby providing an initial assessment of the overall potential. The most promising cases can then be selected for more detailed investigations to verify actual availability and assess technical, economic, and organisational feasibility before proceeding to design or investment stages.

In a broader perspective, aligning effectively with EU decarbonisation objectives requires robust planning instruments capable of quantifying and mapping WH and renewable energy potentials. The presented methodology offers a practical and replicable solution to support scenario analysis and decision-making for modernisation, DH development and planning-stage assessment in the context of the urban energy transition.

Nomenclature

Table 4: List of the main symbols used in the manuscript, including their explanation and corresponding units.

Symbol	Explanation	Unit
A	Footprint area of the building/facility	m ²
COP	Coefficient of performance of the refrigeration/heat pump system	–
h	Hourly time-step index over the year	–
i_T	Temperature-level index in the industrial waste heat database	–
i_e	Employee-size class index in the industrial waste heat database	–
$i_e^{min}, i_e^{max}, \bar{i}_e$	Lower and upper bound, and average of the employee-size class	–
Δi_e	Interpolation interval associated with employee-size class $[\bar{i}_e, \bar{i}_{e+1}]$	–
Ir	Piecewise linear interpolation function used to estimate industrial waste heat	MWh y ⁻¹
n_e	Actual number of employees of the industrial facility	–
n_f	Number of floors of the building	–
q^{WH}	Specific annual waste heat potential per unit area	kWh m ⁻² y ⁻¹
Q^{WH}	Waste heat potential for source/activity type and temperature level	MWh y ⁻¹
s	Source, activity-type, or industrial sector index	–
T, (T_L, T_M, T_H)	Waste heat temperature (low-temperature, medium-temperature, high-temperature)	°C
y	Annual aggregation index	–
α_h	Dimensionless hourly availability profile for source/activity	–

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Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used AI tools in order to improve language and readability. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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