



## **Waste Heat Assessment and Resource Mapping**

A data-driven approach to investigating heat recovery potential from cooling applications

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**REnewable Energy for Future UK Net-Zero Cooling (Reef-UKC)**

## 1. Introduction

The reuse of waste heat from cooling in several industrial and commercial applications represents a great opportunity for reducing primary energy consumption. The advent of 4<sup>th</sup> and 5<sup>th</sup> generations of district heating and cooling (DHC) have unlocked the potential for integrating cooling systems to DHC networks with different temperature levels, paving the way for large-scale decarbonisation of urban areas. Although some case studies have been implemented to date, heat recovery projects often face unique challenges to their implementation, which typically results from specific incentives (e.g. grants, subsidies) rather than propitious market conditions. Some of these challenges include:

- High electricity costs, leading to long payback periods;
- High costs of recovery and lack of standardised commercial arrangements;
- Uncertainty over longevity and stability of the waste heat sources;
- Spatio-temporal mismatch between heat production and demand;
- Access to data on existing heat sources, their location and potentials.

The WHARM project was aimed at addressing some of these barriers by developing a georeferenced waste heat database for the West Midlands Combined Authority (WMCA) metropolitan area, with a focus on cooling applications such as data centres, transformers, cold stores and supermarkets. The database includes information on key parameters that define the feasibility of heat recovery projects, such as annual heat output, temperature level, typical connection/generation costs, etc. The database is plotted on an online GIS map that can be accessed freely and used to inform feasibility studies and the development of business models for future heat recovery schemes. It is publicly available online and can be accessed via the following link: [West Midlands Heat Source Map](#).

## 2. Context and background

The Reef-UKC network aims to support the next generation of renewable energy technologies to meet future cooling demands. While doing so, Reef-UKC is also focussed on promoting system-level thinking, circularity and energy efficiency. One important aspect of future energy systems which relates to this ambition is exploring synergies between heating and cooling applications, particularly as consumers transform into “prosumers”, i.e. both producers as well as users of energy in its various forms [1].

The 4<sup>th</sup> and 5<sup>th</sup> generations of DHC are characterised by low operating temperatures and can combine heating with cooling provision either at source (4G) or building (5G) levels [2]. In many applications, large-scale heat pumps (HPs) can be used to recover heat whilst simultaneously providing cooling (e.g. in data centres [3], supermarkets [4], electrical substations [5] and railway tunnels [6]). This “prosuming” approach enables heating and cooling infrastructure to be shared, reducing overall energy costs and improving resource efficiency.

For this reason, opportunities for heat recovery at low temperatures (<100°C) have been increasingly reported in the literature in recent years, particularly with the advent of 4G and 5G networks. These novel generations have accelerated the uptake of so-called unconventional heat sources for district heating (DH), which have the potential to meet a significant share of the UK’s building heat demand. This was highlighted in a recent study by Davies et al. [7], which estimated there is around 53 TWh p.a. of untapped potential for low-temperature recoverable heat in the UK. At a European level, the ReUseHeat research project investigated a range of heat sources and estimated the potential to be 1410 PJ (392 TWh) per annum of recoverable waste heat, considering the 28 EU countries as per 2019 (including the UK) [8]. This represents a unique opportunity for accelerating the transition towards clean, affordable, and efficient heating systems in the future.

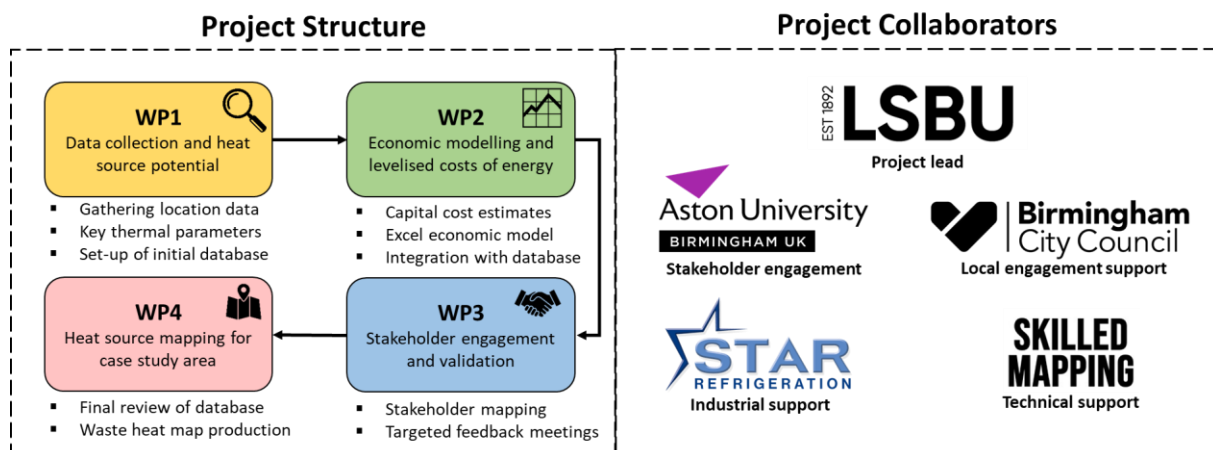
The UK is perceived as a key emerging market for DHC, with a government target to increase the share of heat demand met with such networks from 2% today to 20% by 2050. This

ambition is also supported by policies such as heat zoning [9] and the Green Heat Network Fund [10]. The UK Government has recognised the importance of DHC to decarbonise heat in buildings, but the potential to integrate cooling remains largely unknown, and our project will address this gap by collecting data and estimating costs of heat recovery from several sources, with a focus on those that involve some form of cooling.

The WHARM project developed a simple yet comprehensive georeferenced database that can indicate the thermal and economic performance of recovering heat from different sources, with the aim of supporting local authorities, energy planners, and DHC developers in quantifying the potential costs of recovering waste heat and either upgrading or using it directly (depending on source temperature). The project also benefits waste heat owners by increasing visibility over their assets and facilitating engagement with potential off-takers. With the WMCA region as its case study, the foreseeable impact of WHARM is to incentivise waste heat reuse and the development of new DHC projects in the metropolitan area.

### 3. Project structure and collaborators

The WHARM project is a collaboration between academic, industrial partners and Birmingham City Council. Academic partners were London South Bank University (project lead) and Aston University (stakeholder engagement lead). Non-academic partners included Star Refrigeration and Skilled Mapping, both providing technical support, as well Birmingham City Council, which had an advisory role and facilitated engagement with stakeholders. The project structure consisted of four main work packages (WPs), as shown in Figure 1.



**Figure 1 – WHARM project structure, highlighting its main WPs, and all partners involved.**

The following section will provide more details of the work carried out in each WP, describing the methodology used to develop the waste heat map for the WMCA metropolitan area.

### 4. Data collection

The aim of the data collection for the WHARM project was to obtain as much information as possible on heat source characteristics and potential cost for recovery and upgrade (when applicable). Heat sources that involve cooling were the focus of the stakeholder engagement (see Section 6), but data available for other types of heat sources were also included in the database. The final list of heat sources includes the following 12 types of heat sources: chemical industries, cold stores, crematoria, data centres, energy from waste (EfW), electrical substation transformers, food and drink industries, iron and steel industries, other mineral industries (e.g. glass, ceramics), paper and pulp industries, supermarkets and wastewater treatment works. The data collected for each heat source type can be divided into three categories, which are listed below and described in detail in the following subsections.

- Heat source data: information on locations, temperatures and recovery potentials for all local sites belonging to each heat source;

- Costs of recovery: average estimates of capital (CAPEX) and operational (OPEX) costs for each heat source type, based on findings from [11]. These were adjusted for inflation from 2020 to 2024;
- Cost of heat upgrade/generation: average estimates of capital (CAPEX) and operation and maintenance (O&M) costs. These were obtained from [12], adjusted based on price level indexes for Denmark and the UK [13], converted from EUR to GBP and adjusted for inflation from 2020 to 2024.

#### 4.1. Heat source and cost of recovery data

The heat source data was obtained mainly from waste heat research commissioned by the DESNZ, which was led by Arup [11], with support from LSBU, and fed into the National Comprehensive Assessment on opportunity areas for district heating and cooling in the UK [14]. More details on the original dataset can be found in [15]. Since completion of this project in 2021, LSBU has gathered more data on specific heat sources through projects such as LoT-NET [16] and TICC [17]. The compilation of data gathered from these sources led to a national waste heat database consisting of 12,489 sites and a theoretical heat recovery potential of 289 TWh per annum. This dataset was then filtered to include only sites located within the boundary of the WMCA, which includes the local authorities of Birmingham, Coventry, Dudley, Sandwell, Solihull, Walsall and Wolverhampton. After filtering, 428 sites were left, with a total heat recovery potential of approximately 4.9 TWh per annum. A summary of the final dataset with key performance indicators (KPIs), including benchmark costs of recovery (CAPEX and OPEX), is provided in Table 1.

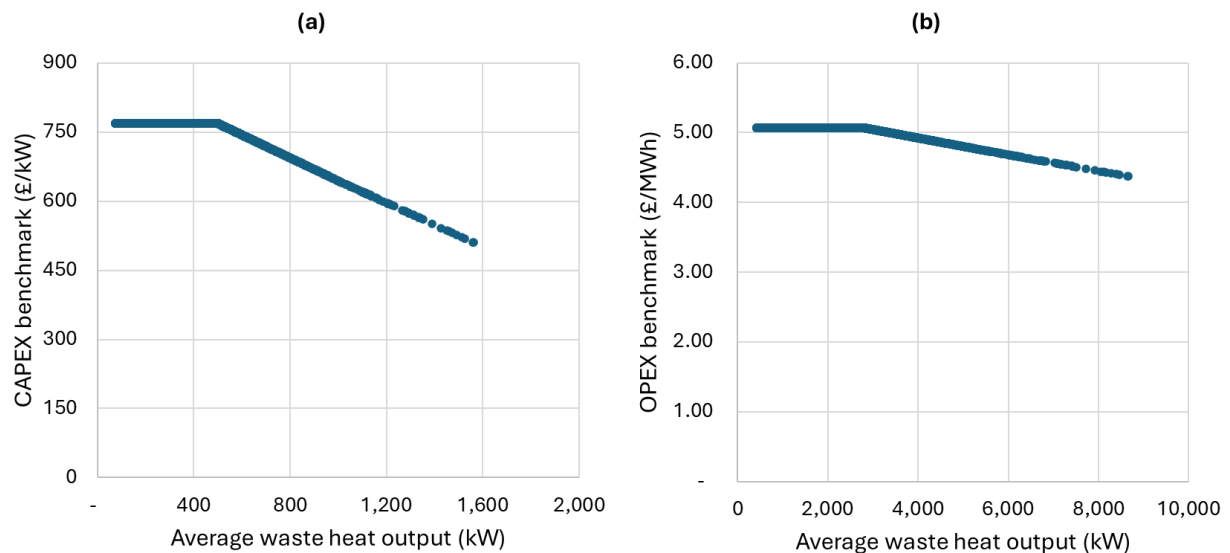
**Table 1 – Summary of heat source and cost of recovery data for the WMCA area.**

Source type	Assumed recovery temperature (°C)	Average heat output (kW)	Estimated recovery potential (MWh/yr)	CAPEX heat recovery benchmark (£/kW)	OPEX heat recovery benchmark (£/MWh)
<b>Energy from Waste (EfW)</b>	90	50,061	368,448	-	-
<b>Crematoria</b>	90	318	713	743	10.35
<b>Iron and Steel</b>	90	28	221	743	5.41
<b>Electrical Substations</b>	40	419	4,237	1,002	4.05
<b>Data Centre</b>	30	1,787	15,652	221	6.40
<b>Other Mineral Industries</b>	30	58	438	223	6.42
<b>Chemical</b>	27	71	532	223	6.42
<b>Paper and Pulp</b>	25	748	5,323	223	6.42
<b>Food and Drink</b>	25	93	694	223	6.42
<b>Cold Stores</b>	18	824	5,542	922	5.44
<b>Supermarkets</b>	18	249	1,380	921	6.11
<b>Treatment Works</b>	13	7,005	58,298	232	6.41

For certain sources (supermarkets, cold stores and treatment works), there was a significant variation in size amongst the selected sites. In such conditions, recovery costs benchmarks also varied considerably, and correlations were used to express economies of scale, in both CAPEX and OPEX, associated with recovering heat from larger sites. This is exemplified in Figure 2, which represents CAPEX (£/kW) and OPEX (£/MWh) benchmarks as a function of

average heat output (kW) for supermarkets. As it can be observed, recovery cost benchmarks were assumed to reduce linearly as heat output increases.

Another point of attention is that no recovery costs were available from EfW plants. Their costs were instead represented as costs of generation for new plants in two modes, combined heat and power (CHP) and heat-only. These will be described in the following subsection.



**Figure 2 – CAPEX (a) and OPEX (b) benchmarks as a function of heat output for supermarkets.**

#### 4.2. Cost of heat upgrade or generation

The recovery cost benchmarks listed in Table 1 include only those associated with the capture of waste heat, i.e. costs of temperature upgrade with a heat pump are excluded. However, HPs are often a major share of the costs for heat recovery projects, and their need is subject to the difference between source and network supply temperatures. To support in estimating the feasibility of waste heat recovery, our approach has been to indicate the levelised costs of delivering heat at the point of connection to the DH/DHC network, which includes both recovery and upgrade costs. This establishes a basis for comparison between waste heat and other generation technologies for DH/DHC (e.g. gas boilers, air-source heat pumps and biomass boilers). The upgrade costs were derived from the technology catalogues from the Danish Energy Agency [12]. Price level indexes were used to transfer these costs to the UK, and both currency conversion and inflation factors were applied to bring figures to 2024 values in GBP. The methodology for updating cost data is described in 4.3.

Cost data for different generation technologies for DH are available in the catalogues. Some technologies have more than one data point covering different sizes (e.g. small, medium and large), whereas others have only a single data point. To represent all of the heat sources considered in this study, the following technologies were considered:

- Heat pump, industrial excess heat (3 data points): considered the technology of choice for chemical industries, cold stores, data centres, electrical substations, food and drink industries, paper and pulp industries, supermarkets and other mineral industries;
- Heat pump, sea water (1 data point): due to its large scale and heat recovery medium, it was used in the estimates for wastewater treatment works;
- EfW CHP (4 data points): used to represent the costs of new CHP equipment for EfW plants;
- EfW heat-only plant (1 data point): used to represent the costs of a new equipment for

an EfW plant operating in heat-only mode (i.e. without electricity generation).

For EfW, due to lack of data, the costs for retrofitting an existing plant with heat recovery equipment were not considered, so levelised costs are only calculated for new equipment. A heat pump was deemed unnecessary for iron and steel industries and crematoria due to the high temperatures that were assumed for their waste heat streams.

From the different data points, linear and power correlations were obtained, in the format indicated in Equations 1 and 2, and used to represent the CAPEX and O&M costs for heat upgrade or generation equipment for waste heat sites of different size. The regression coefficients (a, b) adopted for each type of technology are shown in Table 2.

$$y = ax + b \quad [1]$$

$$y = ax^b \quad [2]$$

**Table 2 – Coefficients used for calculating costs of heat upgrade and generation.**

Technology	y	x	a	b	Correlation
Industrial excess heat HPs	CAPEX (£/kW <sub>th</sub> )	Capacity (MW <sub>th</sub> )	1,176	-0.266	Power (2)
	Variable O&M (£/MWh <sub>th</sub> )	Capacity (MW <sub>th</sub> )	2.66	-0.202	Power (2)
	Fixed O&M (£/kW <sub>th</sub> )	Capacity (MW <sub>th</sub> )	0	1.97	Linear (1)
Seawater HPs	CAPEX (£/kW <sub>th</sub> )	Capacity (MW <sub>th</sub> )	0	467	Linear (1)
	Variable O&M (£/MWh <sub>th</sub> )	Capacity (MW <sub>th</sub> )	0	1.17	Linear (1)
	Fixed O&M (£/kW <sub>th</sub> )	Capacity (MW <sub>th</sub> )	0	3.94	Linear (1)
EfW CHP	CAPEX (£/kW <sub>in</sub> )	Capacity (MW <sub>e</sub> )	3,067	-0.14	Power (2)
	Variable O&M (£/MWh <sub>in</sub> )	Capacity (MW <sub>e</sub> )	-0.001	5.80	Linear (1)
	Fixed O&M (£/kW <sub>in</sub> )	Capacity (MW <sub>e</sub> )	210.6	-0.412	Power (2)
EfW heat-only	CAPEX (£/kW <sub>in</sub> )	Capacity (MW <sub>th</sub> )	0	1,789	Linear (1)
	Variable O&M (£/MWh <sub>in</sub> )	Capacity (MW <sub>th</sub> )	0	7.67	Linear (1)
	Fixed O&M (£/kW <sub>in</sub> )	Capacity (MW <sub>th</sub> )	0	81.02	Linear (1)

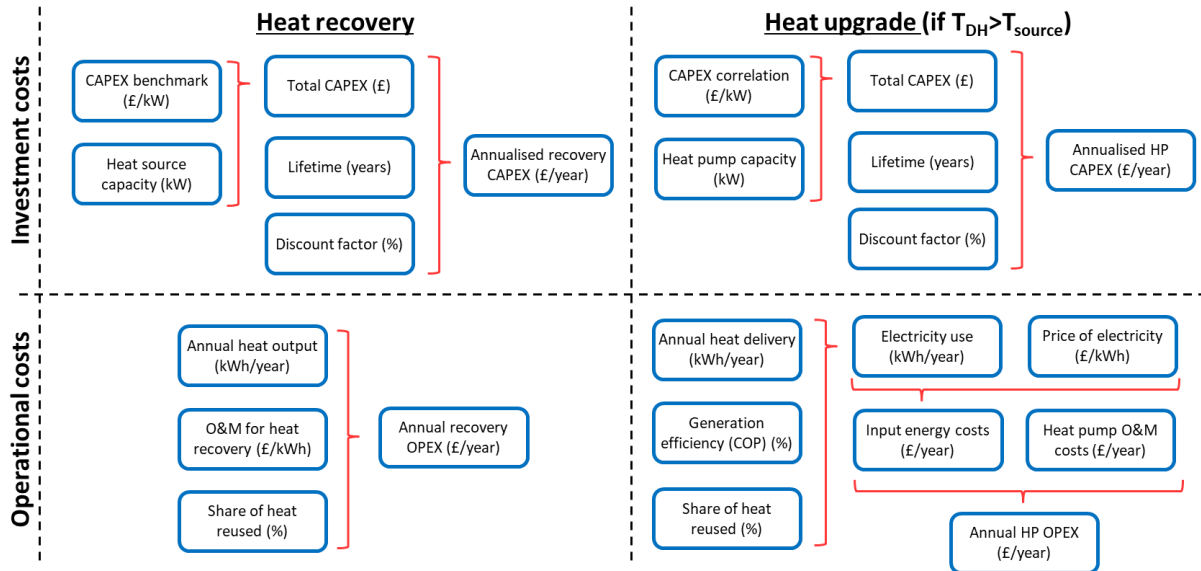
\*Subscripts: th = thermal; e = electrical; in = energy input (incinerated).

### 4.3. Currency conversion, inflation and price levels

The transferring of cost data to current UK price levels followed the methodology used in the FAST DHC project [18]. This involved applying purchasing power parities (PPPs), which compare price levels between countries, for estimating the cost of comparable technologies across countries, and inflation datasets for adjusting for inflation from the date of the technological data to the date of the analysis. The factors applied for PPPs are derived from Eurostat's datasets for Machinery and equipment (A0501) and Civil engineering works (A050203). While the former was applied to CAPEX data, the latter was the closest possible description and assumed to be applicable to O&M data. Therefore, factors of 0.89 and 0.90 were used to transfer price levels from Denmark to the UK for CAPEX and O&M costs, respectively. An inflation factor of 21% was calculated based on consumer price indexes for industrial goods and services in the UK [19]. Final costs were converted from EUR to GBP using a factor of 0.85.

## 5. Economic modelling

The WHARM economic model combines the costs of heat recovery and upgrade or generation to provide an estimate of the levelised costs of heat production at the point of connection to a DHC network. This approach follows a modular structure and combines CAPEX and OPEX figures linked to both recovery (section 4.1) and upgrade or generation (section 4.2) stages. Figure 3 illustrates how the different cost elements interact to produce the levelised costs estimates under the WHARM economic model.



**Figure 3 – Investment and operational cost elements for both heat recovery and upgrade.**

Together with the data described in Section 4, additional calculations and inputs (hypotheses) from the user are needed to be able to estimate the levelised costs of heat production from different heat sources. The levelised costs of heat (LCH) are calculated using Equation 3.

$$LCH = \frac{CAPEX_a + OPEX}{Q_{out}} \quad [3]$$

Where:

- $Q_{out}$ : heat output from source after upgrade (if applicable) using Equation 4;
- $CAPEX_a$ : annualised CAPEX, calculated using Equation 5;
- OPEX: sum of O&M (see Table 2) and electricity costs ( $C_{el}$ , Equation 6) if applicable;

$$Q_{out} = \frac{SR \cdot Q_{rec}}{1 - 1/COP} \quad [4]$$

$$CAPEX_a = CAPEX \cdot \frac{r \cdot (1+r)^n}{(1+r)^n - 1} \quad [5]$$

$$C_{el} = \frac{Q_{out}}{COP} \cdot P_{el} \quad [6]$$

Based on the selection of the DHC network typology, the HP's coefficient of performance (COP) is then calculated, if the DHC supply temperature is higher than the source temperature (see Table 1 for reference), using Equation 7.

$$COP = \frac{T_{Sink} + 273.15}{T_{Sink} - T_{Source}} \cdot \eta \quad [7]$$

Where:

- $T_{Sink}$ : required output temperature, defined based on DHC typology selected;

- $T_{\text{Source}}$  : temperature of the waste heat source, as shown in Table 1;
- $\eta$ : system Carnot efficiency factor, assumed as 50%.

If the network supply temperature is lower or equal to that of the source, it is assumed that no HP would be needed and the heat output is equivalent to the estimated recovery potential ( $Q_{\text{rec}}$ ) multiplied by the share of share of heat reused (SR). In that case, heat upgrade CAPEX and OPEX elements are also excluded from LCH calculations (see Figure 3). The SR and other factors used in calculations are obtained from user selections and are described below:

- **Share of heat reused** (0 to 100%): defines how much of the available waste heat is delivered to the network annually. Impacts OPEX and levelised costs calculations;
- **DHC network typology** (3G, 4G or 5G): Defines the supply temperatures of the heat network the source is connected to. This affects sink temperature assumptions (80°C for 3G, 65°C for 4G and 25°C for 5G) used in efficiency/COP calculations, thus impacting electricity costs. It is important to note that the 5G option does not consider the costs of heat upgrade with decentralised HPs at building level;
- **Price of electricity** (0 to £1000 per MWh): Defines the price of electricity used to calculate the annual electricity running costs for HPs when needed ( $P_{\text{el}}$  in Equation 4);
- **Equipment lifetime** (20 to 40 years): Defines the assumptions of equipment lifetime for all considered elements (heat recovery and upgrade). This impacts the estimates of annualised CAPEX ( $n$  in Equation 4);
- **Discount rate** (0 to 10%): Defines discount factor assumed for all calculations of annualised CAPEX ( $r$  in Equation 4).

These editable inputs represent a key feature of the WHARM tool, enabling users to adapt values based on changing contexts and future conditions, which can have significant impacts on the feasibility of heat recovery projects. One example is the price of electricity, which is projected to increase due to non-commodity costs [18], with disastrous effects on the viability of large-scale heat pumps. Similarly, the type of DHC network can also affect the costs of upgrading heat, and low-temperature networks (4G, 5G) should be prioritised in future developments. Although 5<sup>th</sup> generation networks might lead to cheaper levelised costs at the source, it is important to bear in mind the additional costs of upgrading the heat with decentralised heat pumps, which will be affected by the service temperature requirements.

For EfW plants, as heat pumps are not applicable, levelised cost calculations are based solely on the cost correlations from Table 2, which provide CAPEX and O&M estimates for new EfW equipment. As EfW plants can operate either in in combined heat and power (CHP) or heat only boiler (HOB) mode, this also needs to be selected by the user. When operating in CHP mode, which produces both heat and electricity, associated costs must be allocated between both outputs to better represent their economic value. This was done by utilising the economic allocation method for CHP systems described in [20], where a cost factor for heat ( $f_q$ ) is calculated as shown in Equation 8. This cost factor is then applied to the total CAPEX and OPEX figures for the CHP to calculate the share of costs that can be allocated to heating production (the remainder being allocated to electricity).

$$f_q = \frac{Q}{E \cdot \left(\frac{C_E}{C_Q}\right) + Q} \quad [8]$$

Where:

- $Q$ : thermal output from CHP unit;
- $E$ : electrical output from CHP unit;

- $C_E/C_Q$ : ratio between the unit economic values of the electrical product and the thermal product of the cogeneration system. The UK spark gap of 4.0 was used in calculations.

The thermal and electrical outputs for the CHP cost allocation were estimated by considering the energy input to each EfW plant, as well as efficiency values reported in the Danish technology catalogues [12] for electricity (22%) and heat (78%) generation in EfW CHP plants.

## 6. Stakeholder engagement

As part of the WHARM project, waste heat owners that operate in the WMCA area were also contacted, with the aim of understanding their appetite towards heat recovery and validate the assumptions used in the economic model. This involved targeted meetings with owners of industrial processes with significant cooling requirements and high waste heat potential. The engagement also focused on sources with higher uncertainty (i.e. electrical transformers). Overall, operators of a data centre, an EfW plant, and the distribution network operator (DNO) for the West Midlands were engaged in discussions. They provided information on installed and average outputs from their specific sites, and these were used to produce loading values that were applied to other locations. The key information provided, which was used as inputs to the economic model, are summarised in Table 3.

**Table 3 – Summary of data collected from stakeholder engagement.**

Source	Operator	Key data collected
Data Centres	DC Owner	IT loading factor of 60%, based on informed IT installed and used capacities (MW <sub>e</sub> ).
Electrical Transformers	Local DNO	Typical average loading factor of 40% for substations, validated with stakeholder. Typical site installed capacities for local grid supply points were also provided (3x 240 MVA).
Energy from Waste	Local Authority	Load factor of 84% calculated from informed installed electrical capacity (MW <sub>e</sub> ) and average output annually (GWh <sub>e</sub> ).

## 7. WMCA waste heat database

The final waste heat database for the WMCA is publicly available online as an interactive map and includes all the 428 sites identified in this project, with a theoretical heat recovery potential of 4.9 TWh per annum. A summary of the results for the entire study area, considering default assumptions, is provided in Table 4.

**Table 4 – Summary of economic model results for identified heat sources in the WMCA area.**

Source type	Average production (MWh)	Heat pump COP	Average CAPEX (£)	Average O&M (£/yr)	Electricity costs (£/yr)	LCOH (£/MWh)
Iron and Steel	111	N/A	20,909	599	N/A	18.1
Energy from Waste	144,494	N/A	119,214,273	2,822,556	N/A	50.4
Crematoria	356	N/A	236,586	3,688	N/A	57.4
Electrical Substation	2,486	6.8	1,049,956	16,736	91,890	75.9
Data Centre	9,869	4.8	2,503,744	76,583	510,738	78.1
Paper and Pulp	3,486	4.2	1,324,745	28,350	206,199	94.2
Treatment Works	42,276	3.2	5,678,124	272,960	3,281,838	94.9
Food and Drink	455	4.2	268,993	4,307	26,893	111.8
Other Mineral	276	4.8	176,654	2,753	14,304	114.1

Industries

Source type	Average production (MWh)	Heat pump COP	Average CAPEX (£)	Average O&M (£/yr)	Electricity costs (£/yr)	LCOH (£/MWh)
Cold Stores	3,838	3.6	1,958,100	26,646	266,718	119.1
Chemical	343	4.4	203,735	3,278	19,286	120.9
Supermarkets	956	3.6	724,934	7,820	66,415	139.6

The results indicate two key parameters in defining the economic competitiveness of different heat sources: temperature and scale/size. Higher temperatures enable higher COPs, which reduce electricity input costs and make sources of high-temperature (e.g. EfW, crematoria and electrical substations) cost effective. The relevance of scale can be observed when analysing, for example, the LCH estimates obtained for wastewater treatment plants, which were lower than the values calculated for some sources of higher temperature, such as chemical and food manufacturing. Another example of the impact of scale is the difference in LCH between cold stores and supermarkets. Although heat recovery costs are similar for both sources (see Table 1), supermarkets end up being more expensive due to their smaller heat outputs, which lead to an increase in levelised costs (see Equation 3).

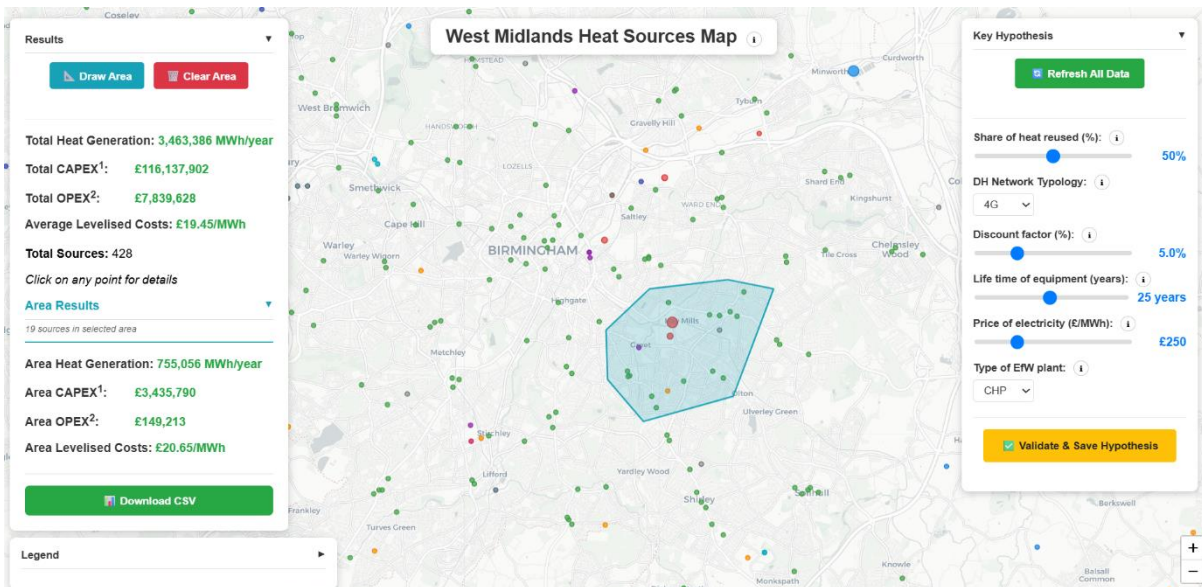


Figure 4 – Visualisation of “Draw Area” feature for result analysis in a selected area.

The WMCA heat map allows users to analyse costs of heat recovery from different sources at the point of connection to a heat network, and users can either click on individual sites to see their associated cost estimates or draw a polygon and obtain the results for all points within its drawn boundary, as indicated in Figure 4. The results for the drawn area can then be downloaded as a CSV file for a more detailed analysis.

### 8. Conclusions and further studies

The WHARM project was aimed at developing a georeferenced waste heat database in the West Midlands metropolitan area, with a focus on cooling applications. The database was designed to help overcome the challenge of lack of awareness and information on waste heat, and includes factors such as heat output potentials, location of waste heat sites, as well as estimated costs for recovery and upgrade. The database has been made available as an interactive online map with the purpose of providing data in an accessible way to local

authorities, waste heat owners and heat network developers.

The database provides evidence on the techno-economic performance of different urban heat sources, establishing a basis for comparison against conventional heating technologies (e.g. gas boilers or air-source heat pumps), and can be used to inform future feasibility studies for DHC projects. The outputs from the economic model provide some insights into how different waste heat sources compare. The most influential factors to the viability of heat recovery are the average size of a source and its temperature, which impact the levelised costs in terms of scale (i.e. how much heat is produced) and operational costs (i.e. electricity needed to upgrade the heat to the supply temperature), respectively. Another important challenge that must be overcome to truly unlock the potential for heat recovery is the high price of electricity, particularly as non-commodity costs are set to rise in the future. District-scale heat pumps are devices that can act as important flexibility assets to the wider energy system whilst decarbonising heat, and policy must recognise that the current structure of the electricity market is hindering progress.

The WHARM methodology is widely replicable to other urban areas in the UK, and it is recommended that future work is carried out to expand its geographical reach, as well as to incorporate additional data relevant to DHC feasibility studies (e.g. local heating and cooling demands and seasonal granularity of supply and demand). Overall, the WHARM project has provided a blueprint for making waste heat data more accessible and useful, thus supporting the transition from fossil-based individual heating technologies to modern concepts of large-scale heat networks, which unlock the potential for electrified, low-carbon, and highly efficient heating and cooling systems in our cities.

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