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Research Paper

Evaluation of low temperature waste heat as a low carbon heat resource in the UK

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ABSTRACT

The capture and transport of waste heat represents a great opportunity for the decarbonisation of heat supply in buildings. To date, mostly high temperature waste heat has been reused and reported. However, with the recent advent of low and ambient temperature (4th and 5th generation) district energy networks, there is scope for the recovery and utilisation of heat from a range of novel, low temperature sources. The current study represents one of the first attempts to quantify the size of this opportunity, with particular focus in the UK, and complements the few previous attempts at estimating low temperature waste heat by focussing on a range of novel sources. The approach used was to evaluate a number of low temperature waste heat sources to determine: (a) the annual quantity of waste heat generated; and (b) the temperature(s) of the waste heat, for each heat source. In many cases, this was achieved using methodology and assumptions derived from the authors' earlier investigations. The relative merits and potential of each heat source are also discussed, with respect to location, proximity to end users, need for upgrade using a heat pump, continuity of supply and distribution options for reuse, for example by using district energy networks with different operating temperatures. The total quantity of waste heat energy identified from the heat sources considered in this study, for England, Wales and Northern Ireland, was estimated to be 572 $TWh.a^{-1}$, which would represent 132% of the total energy consumption for heat in these countries (432 $TWh.a^{-1}$). Although this study focused on the UK potential for low temperature waste heat, the estimation methods developed and resulting analysis are generic and could also be applied in the context of other countries.

1. Introduction

Reducing carbon emissions from heating is a key priority for achieving the UK's target of net-zero emissions by 2050 [1], since at present heat generation is mainly fuelled by natural gas, and accounts for 33% of current emissions. Addressing this issue will require the development and adoption of a range of new and novel low carbon heat sources. One option is to capture and reuse waste heat that is currently released to the atmosphere. Waste heat arises from virtually all energy using (energy transforming) processes, but to date, mostly industrial waste heat at high temperatures (>400 °C) or medium temperatures (100–400 °C) have been considered as having value for reuse. Typically, such waste heat has been used directly, e.g. for conversion to electricity, or reused in the same or in other industrial processes. The opportunity for recovering industrial waste heat in the UK has been widely reported in the literature [2,3], whilst the potential value of low temperature (<100 °C) waste heat, e.g. in terms of quantity and number of sources, has not been widely evaluated and recognised to date, particularly in a UK context.

A few previous attempts to evaluate low temperature waste heat (<100 °C) have been reported, although they focused on different heat sources to those considered here, so the present study complements the earlier work. The previous evaluations included a USA study [4] considering waste heat from a range of industries, namely the power industry, chemicals, petrochemicals, plastics/rubber, primary metals manufacturing, food production, non-metallic minerals, paper and pulp manufacturing and transportation. All produced heat at a wide range of temperatures, with some at low temperature (<100 °C), however, the power generation industry produced particularly large quantities of low temperature waste heat. A second study in China [5] focussed on waste heat from the cement, iron and steel and glass industries and found a significant proportion (approximately half) of the waste heat to be low temperature (close to ambient). A third study for the European Union (EU) as a whole, including the UK, for 2018 [6], considered power generation, mining, minerals, metals, chemicals, pulp and paper and food. This study also showed significant quantities of low temperature

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waste heat, most notably for the power generation sector, which accounted for 95% of the low temperature waste heat for these industries. The USA and EU studies [4,6] used a similar top-down approach to estimating waste heat based on the total energy use of the sector and the energy efficiency of the industrial processes, while the China study [5] relied on expert interviews/questionnaires and literature reviews. In the present study, a different approach was used, namely collecting data on the performance i.e. energy use and waste heat output for many individual sites for the selected waste heat sources. This could be termed a bottom-up approach.

Recent studies of waste heat availability in the UK mainly concerned industrial waste heat sources at a wide range of temperatures from high to low e.g. [3,7], and [8]. Another study has investigated waste heat opportunities in Scotland [9], however, the current paper focuses on the availability of a range of low temperature waste heat sources in the UK, excluding Scotland, but covering England, Wales and Northern Ireland (EWNI), and explores less conventional heat sources that haven't been investigated and compared on a national scale to date. The heat sources selected consisted of waste heat from a range of commercial and industrial processes, and natural sources e.g. geothermal heat, with potential for recovery at low temperature (<100 °C). In addition, they were widely distributed across the UK, although usually located within or close to centres of population, providing opportunities for distributing recovered heat to potential users. All of the heat sources selected have been previously identified as having potential for providing significant low temperature heat resources, and in many cases possible waste heat recovery systems proposed. However, no detailed evaluations of the total heat available from these sources, for all sites in the UK, have been identified. The heat sources evaluated in the present study were data centres, electrical substations, wastewater, mine water, supermarket refrigeration, cold stores and underground railways. All of the heat output from these sources was low temperature i.e. between ambient and 100 °C, although with some variation in these temperatures for each source, both daily and seasonally. Data reported for each heat source include: (a) the source of waste heat; (b) temperature(s); (c) number of heat sources; (d) method of calculation of heat source size; (e) total annual thermal energy output (for the selected heat source type) for EWNI; (f) breakdown of the percentage of annual heat output that is available within local authorities classified as predominantly urban [10]. Source-specific methodologies were employed to estimate the different heat source quantities, involving calculations and assumptions derived from detailed case study investigations undertaken by the authors. In each case, the evaluation method and input data used is described, and the resulting estimated annual quantity of waste heat in TWh.a^{-1} is reported. A summary of the methodology applied and the data sources utilised for each of the investigated heat sources is provided in Table 1. Where applicable, the annual thermal energy output was divided in groups covering specific percentiles (<20th, 20th–40th, 40th–60th, 60th–80th, >80th), in order to represent the distribution of waste heat between sites of different sizes. Subsequently, the results for total thermal energy output for the selected heat sources, at a range of temperatures, for EWNI are summarised in the form of a novel bubble chart and compared to the total heat demand.

The low temperature waste heat application with greatest potential for reducing carbon emissions is for space or hot water heating in buildings, which are alone responsible for 23% of UK emissions [34]. A number of other uses for low temperature waste heat have been suggested e.g. adsorption cooling, separation and purification using membrane distillation and adsorption desalination, and electricity generation, for example using reverse electrodialysis [6]. However, efficiencies for these processes are quite low, so for the present study the focus will be on delivering space heating and hot water i.e. contributing to meeting heat demand.

Recovering low temperature waste heat from a particular source generally involves transferring the heat to water, which is then upgraded to a desired temperature using heat pumps, before distributing the heat recovered using a local (or district) heat network to supply a range of users. Traditionally, heat networks operated with high temperatures (1st to 3rd generation networks) and upgrading low temperature waste heat to the network temperature was not considered economic. However, the advent of lower temperature 4th and 5th generation (4G and 5G) networks [35] has greatly increased the opportunities for recovering low

Table 1
Summary of methodologies and data sources utilised for each investigated heat source.

Category	Heat Source	Waste heat calculation methodology	Initial size of data set	Size of data set after threshold applied	Summary of data sources
Electrical systems	Data centres	Potential determined from declared IT load or estimated from reported white space areas and typical PUE values.	261	261	Publicly available data sheets for individual data centres compiled together, including from manufacturers [11] and sector-specific portals [12,13].
	Electrical substation transformers	Potential determined based on assumed loading factors and heat loss factors from transformer nameplates.	5794	1336	Substation fleet data were obtained from personal communication and online network connection maps, e.g. [14,15]. Data were obtained for each of the 7 DNOs as well as the TNO operating in the UK.
Water resources	Wastewater treatment plants	Potential determined by converting load entering values, in population equivalent, to volumetric flow rates, and then applying a heat extraction rate.	1674	985	Data on entering load for all WWTPs in the UK above 2,000 PE, based on the EU's Urban Wastewater Treatment Directive [16], and heat extraction rates obtained from literature [17,18,19].
	Mine water	Potential determined based a pro-rata approach relating number of mines with total area per country, and then applying an average heat extraction rate.	18,584	18,584	Data on number of mines obtained from [20], whilst coverage areas per country were obtained from the literature [21–23]. Average heat extraction rate estimated from an existing UK case study [24].
Refrigeration systems	Supermarkets	Potential determined by applying typical COSP and refrigeration energy consumption factors to store annual energy consumption, which was obtained based on floor area data.	4853	1424	Typical specific energy consumption values, refrigeration energy use factor and COSP obtained from the literature [25–28], whilst floor area data for England and Wales obtained from the Valuation Office Agency.
	Cold stores	Potential determined by applying typical COSP and specific volumetric energy consumption values to surveyed data on cold store volumes.	241	193	Typical COSP, specific energy consumption and cold store volumes obtained from a previous study carried out by one of the authors from this study [29].
Underground railways	Ventilation shafts	Potential determined based on heat recovery rates from case studies, which were extrapolated based on vent shaft flow rate data from railway operators.	65	65	Heat extraction rates obtained from previous case studies [30,31], while flow rate and ventilation shaft location data obtained from a feasibility report by Transport for London [32] and personal communication with Tyne and Wear Metro [33].

temperature waste heat (and the number of sources), much of which can be transferred directly to the network (using a heat exchanger), without first upgrading using heat pumps. For example, 4G networks typically operate with supply temperatures of 50–60 °C, and 5G networks, which are often termed ambient loops, typically operate with supply temperatures of 15–25 °C. For 5G networks, the heat is distributed (using water) at a low temperature, minimising heat losses, before upgrading close to the user, by means of a heat pump, in order to supply heat at temperatures that are acceptable to the user for space heating and hot water, although often lower than has been conventionally used. To deliver the same amount of heat at lower temperatures, a greater temperature difference between the supply and return temperatures (to the users), than for conventional heating systems may be needed, since the radiator is likely to be less effective at delivering heat at lower temperatures. In addition, the installation of larger radiators for heat users may be required [36].

The Green Heat Network Fund [37] provides financial support for the development of new and existing low carbon heat networks in the UK. It specifies that when developing such a network, at least 2 $GWh.a^{-1}$ of additional heat load (or heat demand), should be forecast for urban networks. However, for rural heat networks, a lower threshold of 100 homes can be applied. 100 homes have a heat demand of 1.2 $GWh.a^{-1}$, based on medium sized homes (2–3 persons), with an average gas (heating) demand of 12 $MWh.a^{-1}$ [38].

If a single low carbon heat source is to supply the additional heat demand (of 2 $GWh.a^{-1}$), this would imply a heat source with an average heat output capacity of 228 kW. In fact, for the current study, a threshold single heat source size requirement of 250 kW and above has been applied for all of the waste heat sources considered.

2. Estimation of waste heat availability from a range of low temperature sources

Details of the waste heat sources considered are provided below, grouped according to heat source type, namely heat from electrical systems, water resources, refrigeration systems, and heat from underground railways.

2.1. Electrical systems

(i) Data centres:

Data centres are buildings, which are usually purpose-designed to provide optimal environmental conditions for the operation of information technology (IT) equipment, such as servers, routers or data storage units. They range widely in size, with power demands typically varying from <10 kW to >650 MW [39]. The IT equipment ultimately converts the input electrical energy into waste heat, due to Joule Heating [40,41]. Due to the temperature sensitive nature of the IT equipment, sophisticated cooling systems are used to discharge heat into the atmosphere using, for example, air cooled chillers or cooling towers [42]. Data centres usually operate for 24 hours (h) a day throughout the year with <1% downtime allowance. Therefore, the waste heat is generated continuously, and at a near constant temperature, due to the strict thermal guidelines under which these systems are required to operate.

Published estimates suggest that data centres are responsible for a significant proportion of the electricity demand for the UK [43–46]. At present, most of the waste heat generated is discarded, however, it could be recovered and reused resulting in significant overall operational cost (OPEX) savings and efficiency improvements [45] and [47]. Since the majority of data centres cool the IT equipment using air, waste heat in the form of heated air, exiting the server racks at 30–40 °C, may be directly used for space heating within the data centre building, or in adjacent buildings. This heat could also be harvested, for example by using an air-to-water heat exchanger, upgraded if required, and then distributed to users via a network. However, this would require significant modification of the data centre infrastructure, so is probably not viable except for new build data centres. An alternative approach is to harvest the heat at 10–20 °C from the chilled water heat rejection line. This would provide lower temperature heat but would be a far less invasive method as the connections would typically be located outside the building, so would be feasible for existing data centres.

Data centres can be broadly divided into colocation type (large data centre facilities serving multiple customers), and enterprise type data centres (owned and managed directly by individual businesses) [48]. However, since colocations are typically larger and details of their specifications can often be found in the public domain, they have been the focus of this investigation. Several online databases which provide publicly declared specifications for colocation data centres were identified, and these together with publications for individual data centres, were used to compile a list of colocation data centre characteristics. These included data such as location, annual power usage effectiveness (PUE) (defined as average ratio of total electrical energy use to IT load, across the year), and white space area (WS), and were collected for a total of 261 facilities. The white space area for a data centre is defined as the floor space area within which the IT server racks, storage, network gear, air conditioning units and the power distribution system are located. In order to estimate the heat outputs of the 261 colocation data centres, the average IT load for each data centre was first calculated. This involved using the WS characteristic for the data centre, an average value for the fraction of WS occupied by IT server racks RF_{WS}, the footprint area occupied by a single rack RF_S, and the average power density per rack R_{PD}, as shown in equation (1).

$$\text{Average IT load} = \frac{(WS \times RF_{WS})}{RF_s} \times R_{PD} \tag{1}$$

where: Average IT load is in kW; WS is in m^2; RF_{WS} is estimated to be 0.18 based on an analysis of 30 data centre reference designs [11]; R_{FS} is 0.642 m^2 [49]; and R_{PD} is 4.286 $kW.rack^{-1}$ [47].

The WS areas used in equation (1) and the annual PUE values used in equation (2) below were obtained from published specification data for the individual data centres considered.

Having determined the IT load, the total electrical energy supplied to the data centre can be calculated by multiplying by the annual PUE. Then, by multiplying by the total number of annual operating hours, the total electrical energy use per annum can be estimated. However, as described by Rasmussen [50], all of the electrical energy used within the data centre is effectively converted to heat and needs to be removed by the cooling system, in order for the temperature of the cooled air entering the IT racks to be maintained. The total heat exhausted from the data centre Q_{dc} can therefore be assumed to be equal to the total electrical energy input. Q_{dc} will include heat output equal to the IT electrical load, heat losses from the uninterruptible power supply (UPS) back up system and power distribution system, heat output equivalent to the lighting power electrical input, and heat output equivalent to the cooling system input electrical power. The total heat output for the data centre can therefore be calculated by:

$$Q_{dc} = \text{Average IT load} \times \text{annual PUE} \times \text{operating hours per annum} \tag{2}$$

where: Q_{dc} is in $kWh.a^{-1}$; and the operating hours per annum for the data centre are assumed to be 8760 (or continuous operation).

Applying equations (1) and (2) to all 261 data centres for which WS values were available, and then summing these Q_{dc} values (for all data centres with a heat output greater than the threshold value of 250 kW, as indicated earlier), the total heat output was calculated to be 16.8 $TWh.a^{-1}$. Approximately 93% of this waste heat is being generated in urban areas, as shown in Table 2, with 63% of the total potential coming from the 20% largest sites, as illustrated in Fig. 1. As indicated above, this heat could be recovered either from the heated air exiting the server racks at 30–40 °C, or from the chilled water heat rejection line at 10–20 °C.

(ii) Electrical substations

Electrical substations consist of transformers that are used for stepping up and down voltage during the transmission and distribution of electricity. The transformation of voltage leads to two types of energy losses in the form of heat, namely no-load losses which are inherent to the transformer and associated with its core; and load losses, caused by the resistance of the windings, which are a direct function of the electrical loading.

Manufacturers provide nameplates for their transformers containing rated values for both types of losses at full capacity, in kW of heat per kVA of capacity. Using nameplate losses for different transformer manufacturers, a correlation was established [51] to estimate the waste heat recoverable from electrical substations as a function of transformer capacity and percentage (of capacity) loading (or fraction L between 0 and 1.0). The correlation was developed by means of a multiple polynomial regression method using loss factors for a range of medium sized transformers. This correlation relates the heat loss with loading and capacity variables and can be used to provide an estimation of waste heat output for any given transformer. For a rated loading of 100% (i.e. L = 1.0) the losses were equivalent to 0.7% kW.kVA^{-1}, which matches closely with the rule of thumb value for transformer losses of 0.5% in thermal kW per kVA of capacity [52]. However, transformers can have several different designs that lead to different levels of heat loss. For that reason, detailed heat recovery design should be performed on a case-by-case basis, and this should be informed by the rated losses factors that are provided by manufacturers in nameplates. The correlation deployed in this study (shown in equation (3) below) should therefore only be used as a high-level tool for indicating the feasibility of heat recovery projects.

$$\dot{Q}_{tr} = C \times (0.0065L^2 + 0.0005) \tag{3}$$

where: $\dot{Q}_{tr}$ is the quantity of waste heat in kW, generated by a given transformer of capacity C in kVA, and subject to a loading L (as defined above).

As waste heat generation (i.e. heat loss from the transformer) is a function of loading L, the calculations are sensitive to the assumptions made regarding the value of this parameter, which depends on the power demand on the substation at any particular time. This uncertainty was accounted for in the analysis by considering a range of loadings from 40 to 50% (L = 0.40 to 0.50), based upon typical values reported [53]. Heat outputs for transformers were estimated based upon individual transformer capacity data and applied to all suitably sized transformers (based on the criteria discussed below), that were identified. Capacity data was obtained for the substation fleets of the seven different Distribution Network Operators (DNOs) in the UK, as well as the National Grid (NG), a Transmission Network Operator (TNO) that manages substations connecting generation plants and the distribution grid. The DNOs included in the analysis are Electricity North West (ENW), Northern Ireland Electricity Networks (NIEN), Northern Powergrid (NPG), Scottish Power Energy Networks (SPEN), Scottish & Southern Electricity Networks (SSEN), UK Power Networks (UKPN), and Western Power Distribution (WPD). The study has focused on the transmission and distribution substations to estimate the potential to recover waste heat from transformers, as electricity generation plant transformers tend to be located in remote areas. Furthermore, data for this type of transformer is not readily available and would have to be obtained directly from the power plant owners. In May 2022, there were 1319 power plants operating in the UK, which are owned by 58 different organisations [54].

In the case of electrical substation transformers, a threshold value of 60 MVA and above capacity at an average loading of 50% (L = 0.5), has been applied. This is equivalent to a total waste heat output of 1.2 GWh.a^{-1} (or 1.6 GWh.a^{-1} delivered, after boosting the temperature with a heat pump, due to the electricity input to its compressor), meeting the lower threshold for rural networks [37]. The reason for using a lower threshold for electrical substation transformers is that the low carbon heat generated is of relatively high quality (>40 °C), and a large number of substations are suitably located within urban areas (58%), with approximately 45% of the heat being generated for the 20% largest substations, which have capacities above 276 MVA (see Fig. 2). However, utilising waste heat from substations, with capacities in the range 60 to 80 MVA might in some cases necessitate combining them with another low carbon heat source, in order to meet the total heat demand requirement of 2 GWh.a^{-1} for urban heat networks [37]. In fact, many electrical substations have more than one transformer, so heat can be recovered from two or more transformers for these sites, enabling the minimum heat demand requirement to be easily met. Also, some transformers may have higher average loadings than the highest figure of 50% (L = 0.5) assumed here, for example 70 or 80% (L = 0.7 or 0.8), which again would allow the minimum heat demand requirement to be met from a single 60 MVA substation transformer. The potential for heat

Table 2
Estimated waste heat from data centres and the shares located in urban areas.

Country	Number of sites >250 kW	Share of waste heat in urban areas	Waste heat output (MW)
England	250	94%	1813
Wales	4	100%	85
Northern Ireland	7	58%	23
Total	261	93%	1921

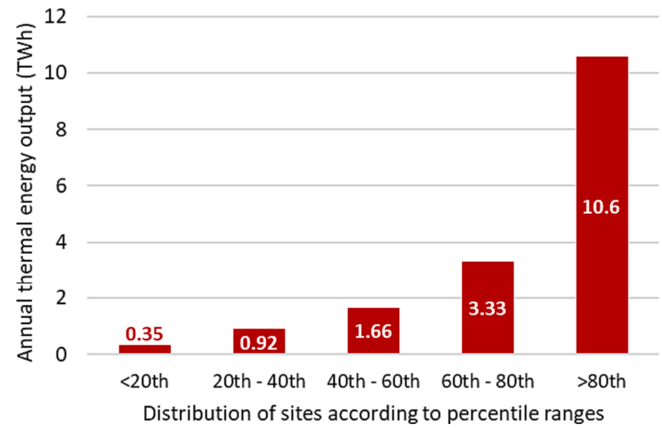

Fig. 1. Total annual waste heat output from data centres for different site size percentile ranges.

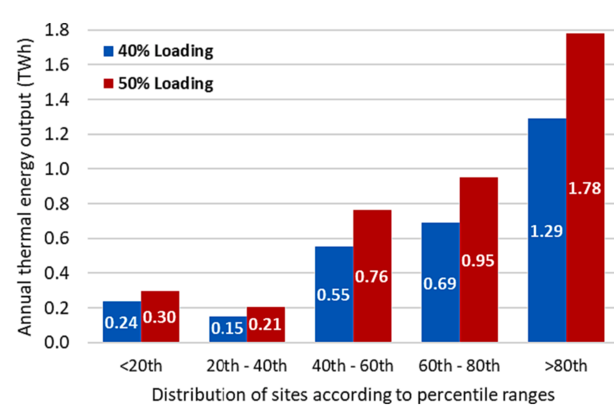

Fig. 2. Total annual waste heat output from substations for different site size percentile ranges.

recovery from transformers should therefore be evaluated on a site by site basis.

The breakdown of waste heat generation located in urban areas and waste heat output for different loadings for each of the three countries is shown in Table 3. The results for annual thermal energy output for the different site size percentile ranges in TWh are provided in Fig. 2. As it can be observed, this heat source offers the potential for very significant quantities of heat to be recovered, estimated to range from 2.9 to 4.0 $TWh.a^{-1}$.

Electrical substation transformers generate significant quantities of waste heat and are often located near to centres of population, and thereby close to large numbers of potential heat users. Recovering waste heat generally involves using water as a heat carrier before transfer to a district heat network (DHN). This can be achieved with heat exchangers that transfer the heat between different (heat) transport systems. Transformers are generally cooled using an internal cooling medium of air or oil, which is circulated through the transformer core by either forced or natural means. The heat carried by the internal cooling medium exiting the transformer is then transferred (using a heat exchanger) to an external cooling medium, namely air or water, which may also be either forced or naturally circulated. Transformers with capacities of >60 MVA usually use forced oil circulation as the internal cooling medium.

Therefore, heat could be recovered from either the internal cooling medium (i.e. oil), or the external cooling medium (i.e. water or air), for example by incorporating an additional heat exchanger and transferring the heat directly to a heat distribution network. Alternatively, the heat could be recovered from the selected location using a heat pump evaporator heat exchanger, and its temperature then upgraded by the heat pump, before transferring to a network for distribution and reuse.

Temperatures for recovered heat from electrical substations are highly dependent upon the loading to which the transformer is subjected. Transformer top oil temperatures are expected to vary from 20 °C to values as high as 70 °C for higher loadings, as described in [53]. Therefore, we have considered a wide range of values in our study that represent the sensitivity of oil temperatures to the load factor of the transformer.

2.2. Water resources

(i) Wastewater Treatment Plants

Wastewater offers the potential of a widespread resource for low temperature waste heat, with wastewater in sewers normally at temperatures greater than ambient. However, wastewater treatment plants (WWTPs) are also attractive locations for waste heat recovery as wastewater flow rates are much higher in the effluent of treatment plants than in sewers [55]. Also, the temperatures may be above ambient, as the biological sewage treatment process results in some heat generation. There were a total of 1877 WWTPs operating in the UK in 2016 [16], with a total of 1674 located in EWNI, representing a large and widespread resource. Measurements from five different plants in London indicated that average daily temperatures for the final effluent typically varied from approximately 12 °C in winter to 23 °C in summer, with an annual average of 17.6 °C [56], so recovered heat from WWTPs would need to be upgraded using a heat pump, prior to reuse.

The recovery of waste heat from wastewater has been investigated by a number of authors, usually focusing on a single plant [57] or city [17]. Recent studies have investigated the potential for recovering waste heat from WWTPs on a nationwide scale, such as Italy [18] and Scotland [9], and a similar approach was applied in the current study. Amongst the 1674 WWTPs, data on load entering the plants, based on population equivalent (PE), was available for all but two WWTPs. Equation (4) calculates volumetric flow rate ($\dot{V}_{ww}$ in $m^3\ s^{-1}$) based on population equivalent (PE), assuming an average daily water consumption of 142 L per person [58]. It was then possible to estimate the potential rate of waste heat recovery ($\dot{Q}_{ww}$ in kW) using equation (5).

$$\dot{V}_{ww} = \frac{142}{1000} \times \frac{PE}{24 \times 60 \times 60} \tag{4}$$

$$\dot{Q}_{ww} = \dot{V}_{ww} \times \rho_{ww} \times c_{p,ww} \times \Delta T_{ww} \tag{5}$$

This calculation assumed a wastewater density (ρ_{ww}) of 1000 kg m^{-3} and a specific heat capacity ($c_{p,ww}$) of 4.2 kJ kg^{-1} K^{-1}. The effect of temperature differences (ΔT_{ww}) between 4 and 6 K was also evaluated. These temperature differences were based on those reported in other studies, such as [17], [18] and [19]. It was assumed that waste heat would be recovered using a water-to-water heat exchanger, or heat pump evaporator heat exchanger, in the effluent stream. The total annual thermal energy output was then estimated, assuming constant operation throughout the year, which equates to 8760 h annually. These calculations were carried out for the 1672 WWTPs for which data were available, with the plants yielding less than 250 kW being excluded from the analysis, as discussed earlier, with the total number of sites varying depending on the heat extraction rate assumed, as shown in Table 4.

Fig. 3 summarises the results from the current investigation indicating the annual thermal energy output, which varied between 14.7 and 22.5 $TWh.a^{-1}$, demonstrating that WWTPs could provide a very significant heat resource in the UK. This potential waste heat is highly concentrated in the largest plants, with sites beyond the 80th percentile accounting for 71% to 74% of the total waste heat output. Not all WWTPs are located in urban areas, however, approximately 67% are, and these sites could be used as an energy source for a DHN.

(ii) Mine water

The mass of water lying in abandoned coal mines, which are the responsibility of the Coal Authority in England, Wales and Scotland, is estimated to be approximately 2.79 billion tonnes contained in 23,000 mines [20]. There are a number of abandoned coal mines in Northern Ireland, which are managed by the Department for the Economy, but less detailed information was available, so they have not been included in this study.

Due to the historical development of towns and cities associated with the coal industry, this resource aligns closely with centres of heat demand, and it is estimated that approximately 1 in 4 homes are built over areas of abandoned coal mines [20]. The total area of abandoned coal

Table 3
Estimated waste heat from electrical substations and the shares located in urban areas.

Country	Number of sites	Share of waste heat in urban areas	Waste heat output (MW)		
			40%	45%	50%
England	1181	57%	292	344	402
Wales	77	69%	25	29	34
Northern Ireland	78	67%	14	17	20
Total	1336	58%	331	390	457

Table 4
Estimated waste heat from WWTPs and the shares located in urban areas.

Country	Number of sites >250 kW	Share of waste heat in urban areas	Waste heat output (MW)		
			4 K	5 K	6 K
England	721–887	66.1–67.3%	294	368	441
Wales	49–58	88.6–88%	22	28	34
Northern Ireland	34–40	39.7–40.6%	14	17	21
Total	804–985	66.5–67.5%	330	413	496

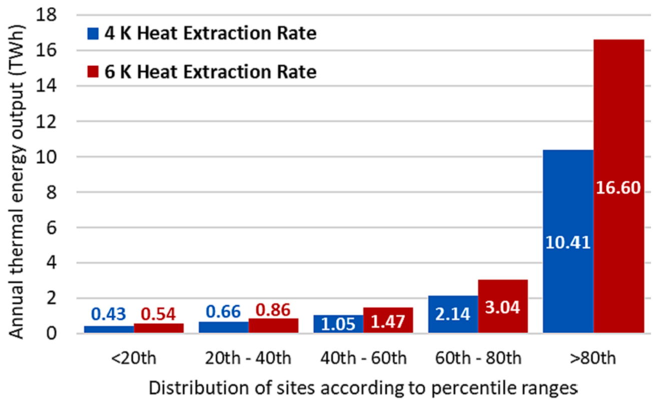

Fig. 3. Total annual waste heat output from WWTPs for different site size percentile ranges.

mines for England, Wales and Scotland has been estimated to be 25,000 km^2 [21], with 3,480 km^2 in Wales [22] and 4,800 km^2 in Scotland [23], so by difference, the area for England is estimated to be 16,720 km^2. For this study, the total potential heat for abandoned mines for England and Wales (EW) was calculated by using the number of mines (estimated on a pro rata basis from their areas), and multiplying by the average heat recovery for a single mine. Due to the approach adopted, results were not represented in terms of the share of waste heat available in urban areas or with a breakdown for different site sizes.

The temperature of the mine water is related to the depth of the coal seams, and the median geothermal gradient in the UK's equilibrium, as found in not actively pumped, abandoned coal mines is calculated to be 24.1 $K.km^{-1}$; however, mean geothermal gradients for different coal mines can vary from 17.3 to 34.3 $K.km^{-1}$, for depth ranges of <100 m to over 1000 m. The deepest seams of >800 m depth, such as in Yorkshire, show temperatures above 40 °C [59]. Mine water can be accessed by drilling boreholes into flooded workings through which water is abstracted. Heat is recovered from this water and its temperature upgraded using a heat pump, before the abstracted water is returned to the subsurface.

One example of a heat recovery scheme for mine water which is under construction is the Seaham Garden Village scheme in County Durham. The recovered heat will be first upgraded using a heat pump and then distributed using a DHN to 1500 houses and a number of community buildings [24]. This heat recovery system exploits an area of circa 125 km^2 and the surface water abstracted is at a temperature of 18–20 °C. The system has been evaluated using abstraction rates of 0.075 and 0.152 $m^3.s^{-1}$ and a temperature difference (ΔT) of 3 K, based on those for the Seaham scheme [24]. In each case, the quantity of heat recovered Q_{mine} is given by:

$$Q_{mine} = \dot{V} \times \rho \times c_p \times \Delta T \times 8760 \quad (6)$$

where: Q_{mine} is in kWh; $\dot{V}$ = volumetric abstraction rate in $m^3.s^{-1}$; ρ = density of water (assumed to be 1000 $kg.m^{-3}$); c_p = specific heat capacity of water (assumed to be 4.2 $kJ.kg^{-1}.K^{-1}$); ΔT = temperature difference between abstracted and return water in K, and the heat recovery system is assumed to operate continuously (8760 $h.a^{-1}$).

The total annual heat output from all abandoned mines Q_{total_mines} in $TWh.a^{-1}$ was estimated using the abstraction rates and temperature differences indicated above, for a single mine, and then multiplying by the total number of abandoned mines in EW (18584). The results for total thermal energy output under these operating conditions are shown in Fig. 4. All mines were estimated to provide >250 kW of heat. Based on the above, the total thermal energy output from mine water was estimated to range from 103 to 519.6 $TWh.a^{-1}$.

Based on the number of mines for each country, 83% of the potential thermal energy output shown in Fig. 4 is in England, and 17% in Wales.

Building on experience in other countries (such as Netherlands, Spain, Canada), more advanced schemes are now being pioneered in County Durham, Tyne and Wear, Northumberland and Nottinghamshire, and by the mid 2020's could provide between 5 and 10 operating systems, each potentially delivering 2–5 MW_{th} [60,20]. The capacity of abandoned mines (and other subsurface aquifers) for thermal storage, or interseasonal storage as part of a heat network scheme, as well as a source of heat has yet to be developed [20].

2.3. *Refrigeration systems*

(i) Supermarket refrigeration

The 10 major UK retail food chains are responsible for 8.4 TWh of annual energy consumption and 4.01 $MtCO_{2e}$ total annual emissions (including refrigerant gas emissions) [25]. Supermarkets are the main retailers of food and comprise a range of store sizes (excluding convenience stores) from 280 to >10,000 m^2 [25]. A significant proportion of the sales floor area is taken up by refrigerated cabinets, both chilled and frozen, and it has been reported that, in general, the refrigeration plant accounts for circa 33% of total electrical consumption for the whole supermarket [26].

The specific energy consumption (SEC) of supermarkets, which is defined as the energy consumption divided by sales floor area (SFA), or total floor area (TFA), has been reported widely, and shows an inverse relationship between SEC and store size. For example, one study [25] found SEC values (based on SFA) varied between 770 and 1480 $kWh.m^{-2}.a^{-1}$, for store sizes ranging from hypermarkets to convenience stores. Another investigation [26] concerned 565 large UK stores with an average SFA of 3,306 m^2, (and average TFA of 5,845 m^2) and estimated a mean SEC (based on SFA) of 566 $kWh.m^{-2}.a^{-1}$, which was calculated to be equivalent to a mean SEC of 320 $kWh.m^{-2}.a^{-1}$, based on TFA. A further investigation [28] studied a further 190 small/medium size UK stores, with an average TFA of 738 m^2, and a mean SEC (based on TFA) of 533 $kWh.m^{-2}.a^{-1}$ was calculated. A survey of supermarkets based on Valuation Office Agency (VOA) data yielded TFAs for 4853 stores in England and Wales. The TFA data were divided into large stores (>750 m^2) and small/medium sized stores (<750 m^2). The TFAs were then multiplied by the appropriate mean SEC (based on TFA) and fraction of total electricity required for refrigeration F_{ref}, to calculate the quantity of electricity used for refrigeration Q_{elec_ref} as shown in equation (7).

$$Q_{elec\_ref} = TFA \times SEC_{mean\_TFA} \times F_{ref} \quad (7)$$

where: Q_{elec_ref} is in $kWh.a^{-1}$; TFA is the total floor area in m^2; SEC_{mean_TFA} is the mean specific electrical energy consumption in $kWh.m^{-2}.a^{-1}$, based on TFA; and F_{ref} is 0.33 (or 33%).

The waste heat generated by supermarket refrigeration comes from refrigeration plant condensers, which is a product of the heat extracted from the refrigeration plant and the power of the refrigeration compressors. The heat output can be calculated by using an average coefficient of system performance (COSP) value, where COSP represents the ratio of cooling load to the total work input to the refrigeration system, including compressor power input, fan power and pump power. The waste heat output $Q_{supermarket}$ can therefore be calculated using equation (8):

$$Q_{supermarket} = Q_{elec\_ref} \times (1 + COSP) \quad (8)$$

where $Q_{supermarket}$ is in $kWh.a^{-1}$; and Q_{elec_ref} is in $kWh.a^{-1}$.

For supermarket refrigeration systems typical COSP values can be assumed to be 4.3 for medium temperature plant, as used for chilled display cabinets, and 1.7 for low temperature plant used for frozen display cabinets [27]. If it is further assumed that 70% of the display cabinets are chilled and 30% are frozen [27], an average COSP of 3.52 for all types of refrigeration system can be calculated. Using equation

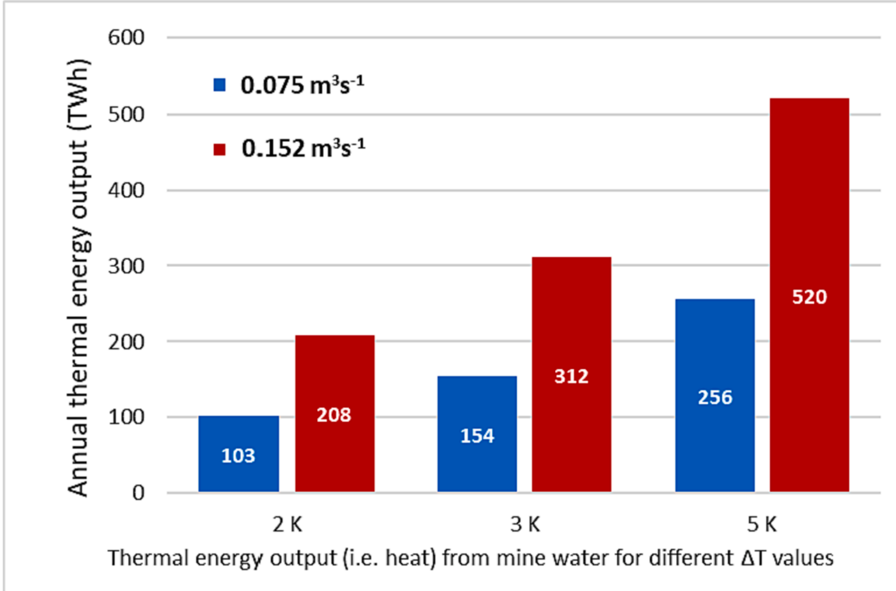

Fig. 4. Potential total thermal energy output for EW.

(8), the $Q_{supermarket}$ value for each of the 4853 stores was estimated. Including only those stores with a heat generation rate of >250 kW (amongst the 4853 stores surveyed), namely 1424 stores, the waste heat values $Q_{supermarket}$ for each of these stores were totalled, resulting in an overall waste heat production of 5.3 $TWh.a^{-1}$, demonstrating this to be a significant heat resource. Most of this waste heat is located in urban areas (70%), as shown in Table 5, and distributed across stores in proportion to size, as illustrated in Fig. 5.

As regards the temperature of the waste heat, there are two main options for capturing the waste heat, namely either directly from the condenser i.e. 74% (or 3.95 $TWh.a^{-1}$), as either air or water, at temperatures of 21–27 °C, or it may be harvested from the circa 26% (or 1.39 $TWh.a^{-1}$) of waste heat available from desuperheating at temperatures of approximately 60–90 °C [61]. The estimated total waste heat generation from supermarket refrigeration reported above is highly dependent on the mean SEC value used to calculate supermarket energy use. However, the SEC values used in the present study are based on detailed investigations using data from a range of stores, namely 565 large stores and 190 small/medium stores [26] and [28]. One advantage of using supermarket refrigeration systems as a waste heat source is that supermarkets are well distributed across the country, located close to the populations they serve, and therefore distributing the recovered heat to users via heat networks should be feasible.

(ii) Cold stores

Cold stores are large refrigerated buildings used to store temperature sensitive products. They may be medium temperature (chilled), or low temperature (frozen), with the required temperature for the cold store maintained by a refrigeration plant. It has been estimated, based on survey and audit data from [29], that approximately 60% of the total electricity consumption of cold store facilities is used for refrigeration.

Table 5
Estimated waste heat from supermarkets and the shares located in urban areas.

Country	Number of sites >250 kW	Share of waste heat in urban areas	Waste heat output (MW)
England	1333	69%	571
Wales	91	83%	38
Total	1424	70%	610

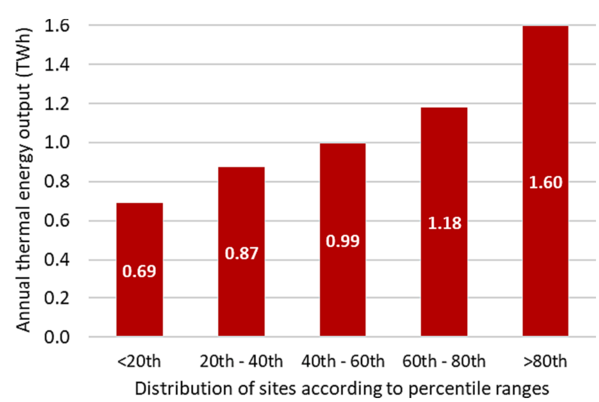

Fig. 5. Total annual waste heat output from supermarkets for different site size percentile ranges.

Only large cold stores were included in the analysis, namely those with >250 kW heat output, to ensure that the minimum heat demand of 2 $GWh.a^{-1}$ for a new network development could be met from a single heat source, as discussed earlier. Cold stores generate significant quantities of waste heat as a result of operation of the refrigeration plant. The heat rejected comprises heat absorbed from the air inside the building (resulting from heat load due to transmission, infiltration, and fixed loads such as fans and defrost heaters), combined with the electrical energy input to the refrigeration compressors.

The main parameter used to characterise the size (and consequently energy consumption) of the cold store is its volume V_{cold_store} in m^3. The volume was multiplied by a SEC_{mean_V} defined as the mean specific energy consumption per unit volume in $kWh.m^{-3}.a^{-1}$ to calculate the total electrical energy consumption of the building. This was then multiplied by the fraction used for refrigeration F_{ref} namely 0.6 or 60% (as indicated above), enabling the annual energy consumption for refrigeration to be estimated. Using survey and audit data [29] for 241 large cold store facilities identified in EWNI, their energy performance was investigated. From the survey data, the volumes for the cold stores were determined, and the mean SEC per unit volume (SEC_{mean_V}) was estimated to be 66.2 $kWh.m^{-3}.a^{-1}$. The electrical energy consumption for refrigeration Q_{elec_cs} or each of the 241 cold stores was then calculated using equation (9).

$$Q_{elec\_cs} = V_{cold\_store} \times SEC_{mean\_V} \times F_{ref} \quad (9)$$

where: Q_{elec_cs} is in kWh.

The waste heat generated by each cold store was calculated using the energy consumption for refrigeration Q_{elec_cs} together with an estimated average COSP value of 1.5 for the refrigeration plant [29], which was applied to both chilled and frozen facilities. The quantity of waste heat Q_{waste_cs} for each cold store was calculated using equation (10).

$$Q_{waste\_cs} = Q_{elec\_cs} \times (1 + COSP) \quad (10)$$

Waste heat from cold store refrigeration plant is usually rejected through desuperheaters and condensers. In the UK, these condensers generally reject 74% of the total heat at temperatures of 21–27 °C. A minimum condensing temperature of 15 °C is needed for hot gas defrosting [62] and [63] for the ammonia refrigeration plant generally used for the larger cold stores. Up to 26% of the waste heat is rejected through desuperheaters on the refrigeration compressor discharge line, at temperatures ranging from 60 to 90 °C.

For the 193 (of 241) stores for which information was available, with Q_{waste_cs} values of >250 kW, the waste heat generated for these cold stores was totalled, resulting in estimates of 2.6 $TWh.a^{-1}$ at 21–27 °C and 0.9 $TWh.a^{-1}$ at 60–90 °C, assuming that heat is recovered from both desuperheaters and condensers, in the proportions indicated above. The total waste heat availability from cold stores is therefore 3.5 $TWh.a^{-1}$. As it can be observed in Table 6, cold stores are not necessarily concentrated in urban areas, which hold approximately 46% of the total heat output. In terms of the waste heat distribution across stores of different sizes, it can be observed that 2.02 $TWh.a^{-1}$ (57%) of the heat is produced by the 20% largest stores, as shown in Fig. 6.

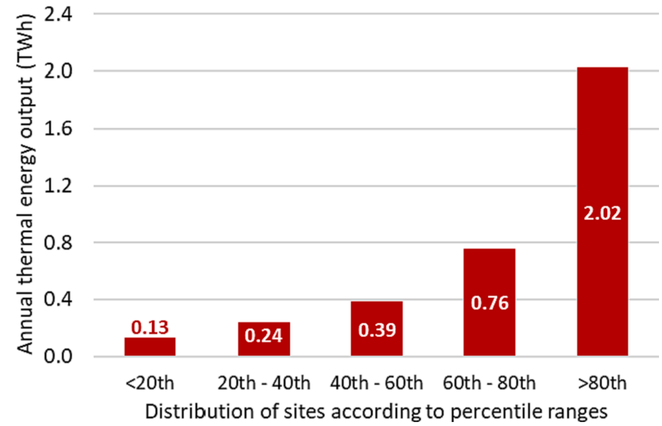

Fig. 6. Total annual waste heat output from cold stores for different site size percentile ranges.

2.4. Underground railways

There is an opportunity for recovering and reusing waste heat from underground railways in cities with metro systems, as the heat generated by trains results in relatively high tunnel air temperatures. For example, a London Underground (LU) study has indicated tunnel air temperatures of 20 °C on a cold winter's day, and up to 32 °C during summer [64]. Another study investigated the potential of capturing waste heat from the Glasgow Subway in Scotland, with tunnel air temperatures of 15 to 18 °C, compared to outside average temperatures of 4 to 16 °C [65]. Amongst many different methods proposed for recovering waste heat from underground railways, placing air-to-water heat exchangers in ventilation shafts represents a viable solution [66].

The potential for recovering waste heat from ventilation shafts across the LU network has been investigated through case studies [66,30]. Both studies involved upgrading the waste heat with large scale heat pumps, before delivering low carbon thermal (heat) energy to nearby buildings via a DHN. One system proposed [30] recovering 900 kW of heat with an air temperature difference of 10 K across the heat exchanger, which was fitted within a ventilation shaft with an air flow rate of 75 $m^3.s^{-1}$. Another study [31] reported a scheme that recovered 780 kW from a ventilation shaft with a temperature difference of 9 K across the coils, at an air flow rate of 70 $m^3.s^{-1}$. The typical heat extraction rate for underground railways, in kW, was calculated considering ventilation shaft air temperature differences (ΔT_{vs}) of 9 or 10 K across the heat exchanger, as reported by the aforementioned case studies. These calculations were also based on typical tunnel air temperatures (for London) of 11 to 28 °C during the year (average of 19.5 °C), and assumed a relative humidity of 50% for tunnel air. There are currently three underground railway systems in EWNI, namely in the cities of, Newcastle, Liverpool and London. However, no data was available for the Liverpool Merseyrail network, so only the Newcastle and London metro systems were considered in the present study. For both cities, the potential rate of waste heat recovery from ventilation shafts ($\dot{Q}_{vs}$) was estimated using the temperature difference benchmarks (ΔT_{vs}) of 9 and 10 K, an average ventilation shaft air flow rate ($\dot{V}_{vs}$) and the number of shafts for each network (N_{vs}), as shown in equation (11).

$$\dot{Q}_{vs} = \dot{V}_{vs} \times \rho_{vs} \times C_{p,vs} \times \Delta T_{vs} \times N_{vs} \quad (11)$$

It has been reported [64] that there may be 113 ventilation shafts with potential for heat recovery in the LU network, consisting of 58 station shafts with an average flow rate of 28 $m^3.s^{-1}$, and 55 mid-tunnel shafts with an average flow rate of approximately 53 $m^3.s^{-1}$. This implies an average air flow rate of approximately 40 $m^3.s^{-1}$ from LU ventilation shafts. Recently, Transport for London (TfL) has identified 55 locations as feasible for heat recovery [32]. For the Newcastle (Tyne and Wear) metro, the network runs underground only in the city centre, with 10 ventilation shafts in total. Tunnel temperatures typically vary from 11 to 21 °C during the year, and the average volumetric air flow rate for the ventilation shafts is 50 $m^3.s^{-1}$ [33]. The potential for recovering waste heat from the London and Newcastle underground railways is summarised in Fig. 7 which reports the number of ventilation shafts (as heat sources) and the annual thermal energy output for each metro system, assuming continuous operation. All sites are located in urban areas and no breakdown based on size of ventilation shafts was provided, as calculations were based on average flow rate values. For each of these ventilation shaft heat recovery systems, the thermal output per site was estimated to be significantly greater than the threshold value of 250 kW.

A significant quantity of waste heat was estimated to be recoverable from underground railway ventilation shafts for the two metro systems considered in the current study, ranging from 0.26 to 0.29 $TWh.a^{-1}$. The recovered heat is generally at temperatures < 20 °C, so is most suitable for use with a 5G network, although it could also be used with a 3G or 4G network if first upgraded with a heat pump.

Table 6
Estimated waste heat from cold stores and the shares located in urban areas.

Country	Number of sites >250 kW	Share of waste heat in urban areas	Waste heat output (MW)
England	184	45%	392
Wales	5	71%	8
Northern Ireland	4	32%	4
Total	193	46%	404

2.5. Summary of data from all sources

The results obtained for all heat sources involved in the current study are summarised in a bubble chart in Fig. 8. The size of each of the bubbles represents the total quantity of heat available from each heat source, however, the position of the bubble along the x-axis represents

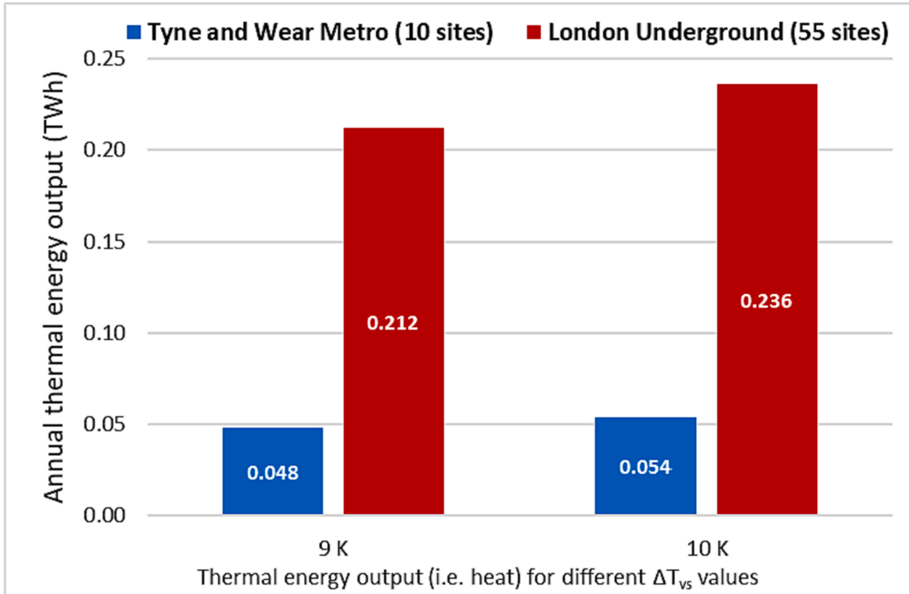

Fig. 7. Summary of results on the potential to recover waste heat from the ventilation shafts for the Newcastle (Tyne and Wear) and London metro systems, considering different temperature differences (heat extraction rates).

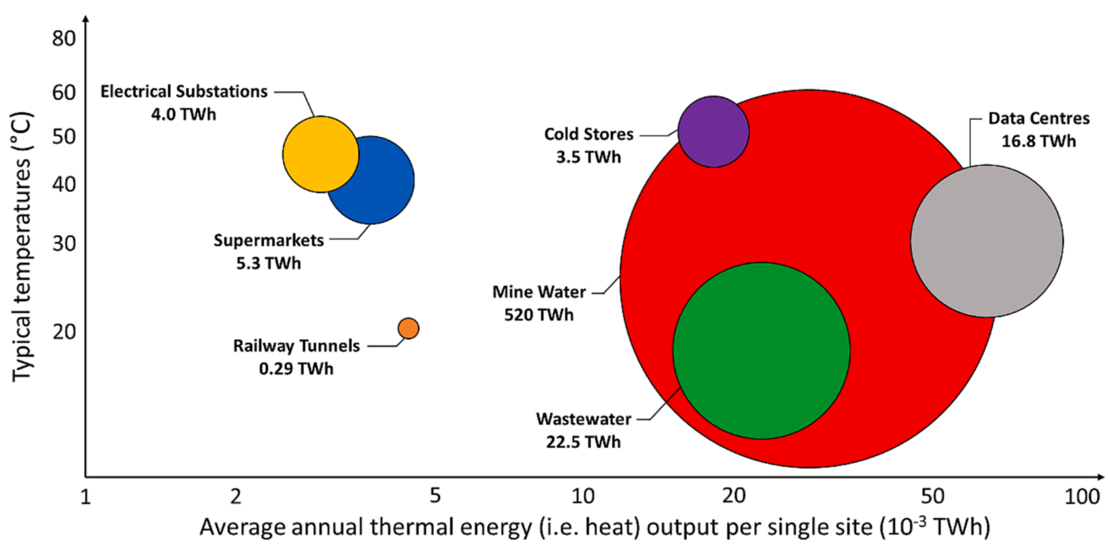

Fig. 8. Summary of total annual thermal energy outputs for heat sources considered.

the average heat output for a single site. Thus, it is seen that mine water provides both the largest total heat availability and the second highest heat output per site. Data centres provide the highest average heat output per site, although the total heat availability is only the third highest of the waste heat sources considered. The position of the bubble vertically within the chart represents the average temperature of the waste heat (including where heat is generated at more than one temperature). All three characteristics, namely total heat availability, heat output per site and temperature, are important in evaluating the overall potential of each waste heat source for use in the supply of low carbon heat. The total annual thermal energy output from all of the heat sources considered in the current study was estimated to be 572.4 TWh.a^{-1}.

3. Discussion

3.1. Estimated thermal energy for low temperature waste heat sources

This study has identified a total of 572 TWh.a^{-1} of potential thermal energy output from the low temperature waste heat sources considered. The current total heat demand for EWNI is 432 TWh.a^{-1} [67], and the annual consumption of energy for domestic heat, which would be the main target for delivering heat to end users is circa 361 TWh.a^{-1} for these countries [67]. This suggests that, in theory, 132% of the total heat demand, or 158% of the domestic heat demand, could be met from these resources. However, in practice the quantity of heat that is economically recoverable, and could actually be utilised, is likely to be lower. For example, the available heat will depend on: (i) the proportion of the total waste heat lost from a process or system that could be targeted for recovery; (ii) the efficiency of the heat recovery process e.g. due to the effectiveness of heat exchangers, the flow rates and temperatures used for the waste heat streams and water loops, pressure drops, pumping power, coefficient of performance of heat pumps (which are affected by a variety of factors); (iii) heat network losses e.g. due to distances between heat sources and demands, operating temperatures, pipe sizes, pumping power; (iv) mismatch between heat output and heat demand, and availability and capacity of thermal storage facilities.

In terms of individual heat sources, water in abandoned mines was by far the largest resource analysed, with an estimated output of 520

TWh.a^{-1} and if harvested from deep levels could provide heat at temperatures of >40 °C, although at levels close to the surface, temperatures are typically circa 20 °C. One advantage of mine water is that it is widely distributed across the UK, with old mines often co-located with residential areas (with 1 in 4 homes built over areas of abandoned mines), for example, flooded coal mines exist below a number of major UK cities, namely Newcastle, Gateshead, Manchester, Sheffield/Rotherham, Stoke-on-Trent and Glasgow [68], so in these cases there is significant heat demand nearby. However, many mines may be remote from urban areas, making distribution of recovered heat via DHNs impractical. A further key issue to be considered is access to the mine water, as many of the former mine shafts have been filled in, and therefore new boreholes are likely to be needed, and are expensive to drill. One approach to developing mine water heat recovery projects is to combine them with existing water treatment schemes, of which there are a number across the country, processing large volumes of mine water. There are also a number of technical issues, most notably the clogging of pipes and heat exchangers by ochre resulting from iron oxides in coal mine water [68], which need to be addressed in order to ensure mine water flows and heat recovery can be maintained.

Although mine water alone could theoretically supply all of the annual domestic heat demand in EWNI, of 361 TWh.a^{-1}, the other low temperature heat sources investigated could also make a substantial contribution (of 53 TWh.a^{-1}), or around 15% of the annual demand for domestic heat.

Wastewater provided the second largest heat resource of 22.5 TWh.a^{-1}, using a temperature difference of 6 K. The current study has focused on recovering heat from wastewater treatment plants (WWTPs). These are widely distributed across the UK and are generally close to centres of population offering the opportunity for distributing the recovered heat to potential heat users through the use of heat networks. The temperature of the recovered heat is low ranging from 12 °C in winter to 23 °C in summer, however, this can be upgraded to the temperature required using heat pumps. The recovery of heat from sewers is also being investigated in Scotland [9], Italy [18], Poland [57], Germany [19] and other countries around the world, and offers the potential to recover heat at slightly higher temperatures. It would also enable heat recovery at an even wider range of locations, although fouling of heat exchangers and potential interference in wastewater flow are known problems, which are avoided when recovering heat from the clean water discharge from WWTPs. Wastewater is expected to be widely utilised as a heat resource in the future.

The third largest source of heat identified was data centres with an estimated total thermal energy value of 16.8 TWh.a^{-1}. Heat could be recovered from either the heated air exiting the server racks at 30–40 °C, or from the chilled water heat rejection line at 10–20 °C. Heat recovery systems are likely to be easier to implement within the chilled water heat rejection line for existing data centres, but could more readily recover heat at higher temperatures from heated air flows, if integrated into new build data centres. This estimate for total thermal energy was based on data for 261 colocation data centres in EWNI. Given the high electrical energy use of data centres in the UK, and the correspondingly large quantities of waste heat and carbon emissions, there is a case for more formal recording of energy utilisation by data centres, which would facilitate the estimation of their waste heat output.

Supermarket refrigeration was the fourth largest potential heat resource, estimated as 5.3 TWh.a^{-1}. Supermarkets are widely distributed throughout the UK, although many are quite small, with only the largest, namely those generating >250 kW of heat, being considered in the current study. These large supermarkets are likely to be close to densely populated areas (70% of the heat output comes from stores in urban areas), having the potential to supply heat to many local users, if the recovered heat is distributed using a network. Most of the heat would need to be recovered at fairly low temperatures, typically 21–27 °C, although it is estimated that up to 26% could be recovered at higher temperatures, of circa 60–90 °C.

Electrical substations were the fifth largest heat source, producing significant quantities of waste heat, estimated to be 4.0 TWh.a^{-1} at an average electrical loading of 50%, and this heat could be recovered at temperatures of 20 to 70 °C. The number of electrical substations with a capacity of >60 MVA considered were 1,336 in total, for EWNI. Most of these electrical substations are located close to centres of population (58% of the heat output comes from predominantly urban areas), so the recovered heat could act as energy hubs (heat sources), for energy networks. Some daily variation in loading, and hence in heat output may occur, however, the electrical substations are expected to operate continuously.

Cold store refrigeration, the sixth largest heat source, could potentially provide waste heat of the order of 3.5 TWh.a^{-1}. There are fewer cold stores than supermarkets, namely 241 for the whole of EWNI, but they tend to be larger facilities than the majority of supermarkets, so the heat recovered from an individual cold store could support a larger heat network supplying more end users. Possible limitations, however, are that they are less frequently located close to centres of population, so may be less suitable as an energy hub for a heat network. Approximately 46% of the total waste heat available is produced by stores in urban areas. Temperatures for the waste heat are broadly similar to those for supermarket refrigeration, with 74% of the heat rejected at temperatures between 21 and 27 °C, and 26% at higher temperatures of 60 to 90 °C.

The smallest heat source (seventh largest) considered was underground railways, which were estimated to generate 0.29 TWh.a^{-1} in total. However, this could be a useful resource in cities where underground railways are in operation, such as London and Newcastle. There is also a metro system in Liverpool, but the underground section is considered to be too small to provide a significant quantity of heat, and no tunnel air temperature data for this metro system was identified during the current study. Recovering heat from underground railways is likely to have greatest potential in London, which has an extensive underground network, with tunnel air temperatures that vary between 11 and 21 °C during the year.

3.2. Issues to consider when recovering heat from low temperature sources

The utilisation of a given waste heat source for district heating purposes is highly dependent upon its geographic distribution. As capital intensive infrastructure projects, district heating networks are more economical in densely populated areas with high heat demands, such as urban centres of population, due to economies of scale. Any heat sources located within urban areas are therefore more valuable from a district heating standpoint. The cost-effectiveness of heat recovery is highly dependent upon the distance between the heat source and potential end users. Therefore, the feasibility of a heat recovery project must be analysed on a case-by-case basis, and should involve investigating nearby heat demands and potential routes of distribution. In a nationwide assessment, it is harder to determine with certainty if a particular heat source is economically attractive. Previous studies have analysed practical potential based on the distance between heat sources and existing district heating networks e.g. [69] As the UK heat network market is quite incipient, covering only 2% of the national heat demand, our approach to evaluate feasibility has been to indicate how many sites of each heat source are located in local authorities defined as predominantly urban. This was done based on DEFRA's Urban-Rural classification [10], which considers areas with more than 74% of the population in urban settlements to be predominantly urban.

Another key factor in the success of heat recovery projects relates to business models. The analysis of trading arrangements for waste heat was outside the scope of the current paper, which was aimed at estimating the theoretical potential for waste heat recovery from a range of unconventional heat sources in the area of interest. Furthermore, other investigations have been carried out that indicate the singular nature of business models for waste heat and the challenge of establishing an overarching commercial structure that could be applied to heat sources with diverse characteristics. For example, one study [70] interviewed several stakeholders in the field, including waste heat owners, and concluded that developing standardised contracts is a difficult task given the specificity of different heat sources in terms of relating, for instance, to their typical temperatures, intermittency and location. In previous work, the authors of this paper have proposed a business model for data centre heat recovery as part of a 5th generation district heating system [35]. For that particular case, the data centre would pay the district heating operators for a cooling service that would involve recovering its waste heat. This was only possible due to significant heat demands being found in close proximity to the data centre. Such an arrangement might not be feasible depending on the location of a given heat source, as well as whether the heat source has a cooling demand (e.g. wastewater treatment plants do not need cooling). Heat sources with cooling requirements that vary seasonally, such as underground railways, would also require a tailored business model that accounts for this variation. Therefore, a proper analysis of potential business models requires a good understanding of local conditions, and should be carried out on a case-by-case basis.

In the case of supermarkets, it is notable that a significant proportion of their total energy use is for space heating and hot water, particularly in winter. Therefore, waste heat recovered from their refrigeration systems can either be used internally or exported e.g. via a DHN. One study [71] suggested that recovering waste heat from a supermarket transcritical CO_2 refrigeration system in Sweden could provide 1.5 times the heat demand for the supermarket, while another study [72] in the UK, involved modelling a CO_2 booster refrigeration system with heat recovery, integrated with the store's heating system and thermal storage and concluded that it had the potential to reduce energy consumption by 17–18% and greenhouse gas emissions by 12–13%, compared to conventional systems. A recent investigation in Sweden [73] also focused on heat recovery from transcritical CO_2 refrigeration systems in supermarkets and concluded that internal heating demand for the store should be prioritized, while extra heating capacity can then be exported. Consequently, the greatest quantities of recovered heat for export will be available in the summer, when internal heating demand is low. This will be a factor in evaluating the potential benefits of using supermarket waste heat as a heat source for a DHN. To estimate the amount of available waste heat for export for a particular site, both the seasonal variation in heat output for the supermarket refrigeration system and the store annual heat demand profile need to be compared. There may be a case for using a higher threshold (than the 250 kW applied during the present study) when considering the potential for using supermarket waste heat to supply a network. However, for a large network using a range of heat sources, any heat supplied by the supermarket may be acceptable, even if intermittent, with heat demand being met from other sources when supermarket waste heat availability is low. A further consideration for supermarket refrigeration is that having a high power density for a waste heat source is an important factor in terms of minimising the cost of heat recovery equipment needed, since the largest heat sources can be collected most economically. Until recently, most medium and large supermarkets used centralised refrigeration systems, usually using R404A refrigerant, however, with the need to move to lower global warming potential refrigerants, some supermarkets have adopted CO_2 refrigeration systems, which are usually centralised, while others have adopted hydrocarbon based systems which need to be distributed to conform to maximum refrigerant charge regulations. Recovering heat from centralised systems is generally both practical and economic, as indicated above, however, recovering heat from distributed refrigeration systems requires more heat recovery equipment, and may not be economic.

Both waste heat recovery from low temperature sources and heat demand by users are likely to vary on hourly, daily and seasonal timescales and non-synchronously. This may limit the quantity of waste heat that can be used at times of low heat demand. There are a number of ways of ensuring heat demand can be met at all time, for example:

1. Appropriate matching of the waste recovery system capacity and heat demand such that the waste heat source can meet heat demand at all times. However, this is likely to result in some of the recovered heat being wasted i.e. not used, at times of low heat demand.
2. Incorporation of thermal energy storage (TES), enabling closer matching of the waste heat source and heat demand capacities, enabling heat demand to be met while accommodating peaks and troughs of waste heat recovery and allowing more waste heat to be utilised. This approach has been investigated in relation to recovery of waste heat from underground railways and delivery through a DHN to meet heat demand [74]. For a 780 kW heat recovery system and 100 m^3 TES, a reduction in levelised costs of 5.7% compared to not using storage was found.
3. The use of an additional heat source e.g. air source heat pump (ASHP) or conventional heating system to ensure heat demand is met at times when waste heat recovery is insufficient.
4. Using a combination of options 2 and 3.

The optimum configuration for maximising the use of recovered waste heat, while achieving maximum cost and emissions savings needs to be determined on a case-by-case basis.

4. Conclusions

The total quantity of thermal energy identified from the low temperature waste heat sources considered in this study, for EWNI, was estimated to be 572 $TWh.a^{-1}$, which would represent 132% of the total energy consumption for heat in these countries (432 $TWh.a^{-1}$). However, the waste heat available for reuse is likely to be less than this for a range of reasons, as outlined in sections 3.1 and 3.2 above. Notwithstanding, low temperature waste heat offers the potential for a very large heat resource, which has not been widely explored to date. There is an urgent need to reduce dependence on fossil fuel based energy sources and minimise carbon emissions, if the UK's target of zero greenhouse gas emissions by 2050 is to be met. Furthermore, moving away from using natural gas for heating and adopting sustainable energy sources should improve energy security and reduce fuel poverty.

This paper has focused on estimating the total heat generated by a selected range of low temperature waste heat sources, listing the assumptions used in calculating their outputs. The results indicate how low grade waste heat can become a key resource to decarbonise the built environment of cities in the UK and elsewhere.

In terms of future work, a further study is needed to determine how effectively this heat can be used. This will involve a detailed investigation of existing and potential new technologies, including performance, cost and carbon comparisons, to evaluate how low-grade waste heat sources can be recovered. The investigation will require data on a case-by-case basis, for example, detailed information on local context e.g. heat demands and existing district heating infrastructure, as well as available equipment e.g. efficiencies (COPs) and capital costs (CAPEX). Such a study is planned by the authors and would be key to identifying and evaluating the feasibility of future low-grade waste heat recovery projects and will be reported in future publications.

CRediT authorship contribution statement

G. Davies: Conceptualization, Methodology, Writing – original draft, Project administration. **H. Lagoeiro:** Conceptualization, Methodology, Data curation, Investigation, Writing – review & editing. **H. Turnell:** Data curation, Investigation, Writing – review & editing. **M. Wegner:** Data curation, Investigation, Writing – review & editing. **A. Foster:** Data curation, Investigation, Writing – review & editing. **J. Evans:** Data curation, Investigation, Writing – review & editing. **A. Revesz:** Conceptualization, Writing – review & editing, Funding acquisition. **A.**

Leiper: Data curation, Writing – review & editing. **K. Smyth:** Data curation, Writing – review & editing. **J. Hamilton:** Writing – review & editing. **H. Cooke:** Writing – review & editing. **G. Maidment:** Conceptualization, Writing – review & editing, Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that support the findings of this study are available online at: https://doi.org/10.18744/lsbu.92wq6.

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