Highlights

Waste heat mapping: A UK study

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- Waste heat from UK industry are mapped to identify potential waste-heat recovery
- UK industrial waste heat was estimated to be 391,000 GWh in 2018
- Waste heat is concentrated in areas of high population density
- Report details the methodology behind and interpretation of the UK waste heat map
- District heating from certain industries could increase reliance on natural gas
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Waste heat mapping: A UK study

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ABSTRACT

The following study considers the spatial distribution, grade and seasonal variation of waste-heat from industrial sectors in the United Kingdom in 2018. Opportunities to offset the emissions caused by heat generation through the use of waste-heat recovery schemes have been examined. Reducing heat waste is a key intermediate step in avoiding climate disaster until fully decarbonised industrial practices have been developed and implemented. The findings of this study are presented as a 'UK waste heat map'. Data containing information on the natural gas consumption of different industries are used as a proxy for waste heat. This report finds that waste heat is concentrated around densely populated areas and areas with a traditionally strong industrial base. Such areas generate a large amount of the waste heat suitable for heat reuse, such as in a district heating scheme. The total waste heat from UK industry and electricity generation is estimated to be nearly 391,000 GWh per year. The data are represented in the accompanying UK waste heat map as point location data and by waste heat per Local Authority. Opportunities have been identified within each major industrial sector to reclaim and utilise this waste heat.

Nomenclature

- AGR - Advanced gas-cooled reactor
- BEIS - Department for Business, Energy and Industrial Strategy
- CHP - Combined heating and power
- DEFRA - Department for Environment, Food and Rural Affairs
- DUKES - Digest of UK Energy Statistics
- EfW - Energy from Waste
- E-PRTR - European Pollutant Release and Transfer Register
- HNDU - Heat Networks Delivery Unit
- RHR - Refrigeration heat recovery

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1. Introduction

In 2018, total non-domestic natural gas (methane) consumption accounted for 571,464 GWh (or 65%) of total UK gas consumption in that year[1]. All this gas was burnt to produce heat. Some of the produced heat was used to drive industrial processes and some was converted to electricity by the power-generation industry. However, the vast majority of the heat was not utilised but emitted as waste.

As 2050 approaches, it is of paramount importance that the UK is able to reach its target to become carbon neutral [2]. Furthermore, if the United Nations Sustainable Development Goals are to be met by 2030, in particular Goal 17: Affordable and Clean Energy, better use must be made of available resources [3]. The way in which the current resource of heat is wasted must be curtailed, thus possible uses for waste heat have been considered in this study.

This report presents the methodology and findings of work carried out in 2018 to produce a map of potential waste-heat sources in the UK. Full data and the interactive Graphical Information Software (GIS) map can be found on the energy charting site MyGrid along with analysis of UK district heating policy [4]. The contribution of this work is the construction of a new framework for presenting the distribution and quantity of waste heat from non-domestic sources in the UK. The novelty of this work is the construction of an accessible format for this data which allows national and local governments as well as private investors and companies to identify sources of waste heat and facilitate planning its reuse. The high level method outlined in Figure 1 provides a template for completing a similar study in any country using data available for the specific region of interest.

Waste heat has various uses, governed mainly by its location, grade, and seasonality. While many industries deploy heat recovery systems, few engage in larger heat networks that supply domestic sources in district heating schemes [5]. Reliable district heating schemes require a sufficient supply of heat in addition to a long-term commitment from all parties. Almost 450,000 UK homes are supplied with heat from approximately 17,000 heat networks in the UK [6]. However, only 3% of the proposals reported in the Heat Network Delivery Unit's (HNDU) 2019 application procedure utilised a 'primary energy source' (heat source) from industrial waste heat [5]. As the literature on waste heat recovery increases and the technology improves, becoming more viable, industry has a decreasing number of reasons not to adopt heat recovery practices.

Waste-heat reduction and reuse have been widely investigated for each major industrial sector. In many, a potential for waste-heat reduction or reuse has been identified. For instance, Buhler et al. [7] identified 23 PJ of potential waste-heat reduction from the chemical industry in Germany. By recovering up to 40% of waste heat from aluminium, steel and ceramic production, a 15% reduction in natural gas use has been identified in Spain, Slovenia and Italy [8]. Previous work often identifies these heat-waste opportunities by conducting efficiency or exergy assessments of sector processes such as that conducted by Hammond et al. [9].

Brueckner et al. [10] classified the methods of analysing waste-heat recovery as top-down/bottom-up according to the data processing. Top-down analyses use high level statistics to produce a low definition snapshot of waste-heat potential, while bottom-up methods use survey or census level data to give high resolution information.

Miro [11] reviewed the existing methods of mapping waste heat and found them to be specified at regional levels or for specific facilities. They collated their review into a global map of countries and included the reported waste-heat potential from each article. Further existing work focuses mainly on generating a single quotable figure for the potential from a sector or region. Hong et al. [12] generated such a figure for Taiwan using a bottom-up model, However, a framework for deploying this research to construct an accessible database that can be used as a political or investment tool is missing from the waste-heat literature.

The novelty of the current research is in using a top-down assessment method with published consumption figures to represent potential waste heat to create a spatial map to facilitate policy making. This assumes that consumption will lead to waste heat which can be predicted using existing methodology. The current methods are extended by combining these published consumption figures with national membership lists to create a bottom-up map of potential waste heat opportunities, with semi-arbitrary values which can be refined by local politicians and investors looking to reduce waste. This blended top-down/ bottom-up approach is characterised by the identification of sites for further investigation and their representation using GIS mapping. Thus building a framework within which a tool can be constructed to reduce wasted heat and aid decarbonisation.

Such high-resolution mapping has only been reported by McKenna in 2009 [13] who constructed a method using EU emissions trading data. This work was continued, compiling existing waste heat literature into a PhD thesis [14]. This study aims to build on these studies, and uses information about current waste-heat recovery practices and a more recent overview of waste-heat availability in the UK. In addition, a framework has been developed which does not rely on a single set of data being reported in a given year. Our methodology can be extrapolated to any region or sector and updated to fit the available data.

By highlighting the areas where waste heat is available and providing a method for providing an estimate of the quantity and quality of waste heat, the current work aims to aid and accelerate the implementation of waste heat recovery programs in the UK and provide a template for similar work across the globe. Further studies at the national or local level will aid awareness and understanding of the challenge and provide a starting point for specific waste heat appraisals and decarbonisation initiatives.

This work is separated into 5 sections aiming to explore and estimate the distribution, quantity and quality of waste heat from UK industrial sectors. Section 2 describes the methodology of the approach to the work and the sectors that have been analysed. These sectors are based on are based on the divisions imposed by the UK's department for Business, Energy and Industrial Strategy (BEIS) reporting and follow the Standard Industrial Classification (SIC) code structure. Section 3 details the distribution of waste heat and the potential for recovery and reuse within each industrial sector. These results are discussed in Section 4. Section 5 details the conclusions and recommendations of the work.

2. Methodology

This section outlines the approach to quantify and spatially represent the waste heat potential of the UK. Figure 1 gives a visual representation of the novel methodology adopted by this study and is explained below.

First, a proxy energy source was selected to avoid the need for a full assessment of the energy consuming processes within each facility where such data were unavailable. This study used natural gas as a proxy for waste heat in all sectors excluding electricity generation.

Then, suitable energy consumption data were identified within the region and sector of interest. Ideally, full access to census-level data of industrial sites would be used in a bottom-up analysis, but no such data were available. The data sets also needed to clearly define the included sectors and the regions of interest, so that emissions from specific facilities could be correctly attributed.

Following this, industrial sites were identified; as survey level data were not available alternative registers of industrial sites were used, ensuring that the sites were included in the energy consumption reporting definition. Various methods were used, as appropriate to each sector.

An energy efficiency value (heat waste as a proportion of energy consumed) was identified by sector at the required reporting level, i.e., national level in this study. Due to the heterogeneity of processes within each sector, a single representative efficiency figure could not be identified for any sectors except 'electricity generation'.

The efficiency values were then applied to the primary energy data (gas consumption) to estimate the waste heat and the waste heat assigned to the spatial level required for reporting. The current study originally aimed to give postcode level reporting of industrial waste heat, however, due to the lack of industry reply and available data, the Local Authority level was chosen as this is the level of governance which interacts with HNDU in the UK, enabling each Local Authority to use our results as reported.

Finally, the waste heat available from each sector in each region was represented in Graphical Information Software (GIS) to provide an interactive online map for policy makers to use.

In addition, this study verified the results using a secondary proxy for waste heat. Carbon dioxide emissions at the Local Authority level were assessed and compared to the waste heat from natural gas.

The UK waste heat map, the interactive tool produced from the methods outlined in this report, is hosted on the energy charting site MyGrid [4]. Full analysis of the UK heat network policy can also be found on the site. Point maps of industrial facilities can also be found here, but are not presented in this work as the interactive features are not compatible for a print journal.

2.1. Bottom-Up Approach

The initial aim of this study was to extract census-level data of industrial gas usage in the UK to apply the bottom-up approach and identify industrial efficiencies to calculate the waste heat from each site individually. However $< 5\%$ of the 400 industrial sites contacted for consumption and efficiency data replied, citing commercial sensitivities. This problem with accessing census-level data was also noted by McKenna [13]. Further, a freedom of information request for data contained in the annual gas survey (AG1 & 2) compiled by BEIS was declined for the same reason. Therefore, a new hybrid approach was developed using a bottom-up analysis of industrial sites in conjunction with a top-down estimate of the amount of available waste-heat

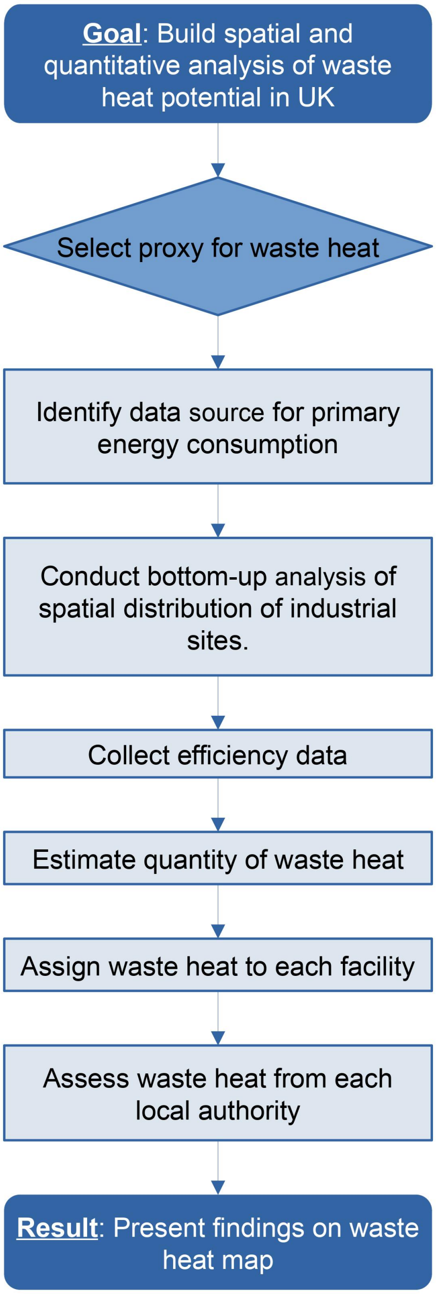


Figure 1: Flow chart of analysis procedure.

2.2. Top-Down Approach

A new, blended, approach was then developed using a bottom-up analysis of industrial sites in conjunction with a top-down estimate of available waste heat quantity. The top-down method to quantify waste heat was built on sectorial reporting from the Digest of UK Energy Statistics (DUKES) on natural gas consumption data. These data disaggregate gas consumption from sectors by the Standard Industrial Classification (SIC) code. However, the use of national consumption figures meant that precisely attributing an amount of waste heat to a specific facility was impossible (as this data was shielded in AG1 & 2). Using site specific efficiencies, if attainable, would have been misleading. Therefore, a single efficiency figure was used to represent each sector and the total gas consumption was split evenly across all identified facilities, regardless of scale, to estimate a representative value of waste heat. Industries and facilities with a high gas consumption were the focus of this study.

A representative efficiency of 30% was therefore used to calculate waste heat. Despite the potentially low level of accuracy, this figure is necessary as the primary function of the map is to provide spatial information rather than quantitative data. The map was constructed from an average of industrial efficiencies reported in the literature and assumes that all appreciable energy waste is lost as heat. Open access reporting on the electricity generation sector is much more complete than other sectors due to government-compiled data on site-specific consumption and efficiencies. Therefore, a sector specific method was followed.

For all industries excluding electricity generation, natural gas consumption was selected as a proxy for heat that is eventually wasted. The most common fuel for industrial heating processes is natural gas, making this an appropriate assumption. The efficiencies and primary fuel consumption within the electricity generation sector is provided as open access reports from DUKES and Elexon and high resolution data were used as available.

The locations of major industrial facilities within each sector were investigated, and are presented, by sector on the waste-heat map. These data were processed and assigned to Local Authority areas, with supplementary point maps detailing the location of industrial facilities for each analysed sector. The number of sites for each industry in a Local Authority area was used as a weighting factor to distribute the total industrial gas-consumption data provided by DUKES for a certain industry across Local Authority areas. This provided an estimate of the waste heat available in each Local Authority area based on the industry in that area. This process was the same for all studied industries. All units of energy are GWh in 2018.

The UK waste heat map contains data from the electricity generation sector based on Elexon half-hourly settlement periods and data from five of the eight largest gas consuming industries; ‘chemical’, ‘food and beverage’, ‘mineral’, ‘vehicle’, and ‘iron and steel’ based on gas consumption statistics from DUKES [1, 15, 16]. Although consumption figures for ‘mechanical engineering’, ‘paper and textiles’ and ‘other industries’ are included in the DUKES data set, they are not included in the following analysis as no comprehensive list of the industrial sites was identified and their gas consumption is relatively small in comparison with electricity generation and the chemical industry. DUKES electricity consumption data show similar, but smaller, industrial consumption trends to those of gas (excluding power transformation). Therefore, electricity was not included in the waste-heat estimate as it would not affect its spatial distribution. Furthermore, such energy consumption is commonly assumed to be negligible in the context of waste heat recovery as the heat recovery potential is often impractically low [11]. Due to the lack of survey data, the availability of waste heat was assumed to be constant throughout the year. Domestic gas consumption and the associated waste heat potential is beyond the scope of this study.

The top-down approach provides the map with comprehensive, albeit low resolution, information about the scale of waste heat in the UK. Exact methodologies for the analysis of each industry are discussed below.

2.2.1. Analysis of electricity generation facilities

Half hourly energy balance data from Elexon were used to estimate waste heat. A parsed and cleaned data set prepared by the Energy Data Analytics Group at the University of Birmingham was combined with DUKES efficiency figures for analysis [17]. The power generation at each half hourly interval was converted into generated energy. Using efficiency figures from DUKES Table 5.10 and other sources, the waste energy has been back calculated to provide an estimate of total waste heat for each fuel type [18]. Using the installed capacities from DUKES Table 5.11, the total waste heat from each power station was approximated. The total waste heat per Local Authority area has been represented on the map. Data for the point map were also taken from Table 5.11 [19].

2.2.2. Analysis of the chemicals sector

Approximated sector waste heat was divided across Local Authority areas identified as the four main clusters of chemical production in the UK namely Hull, Teesside, Runcorn and Grangemouth [20]. Facilities outside of these areas were disregarded as their contribution to waste heat is too small to have a noticeable effect on the mapped distribution. A point map of large chemical plants and petrol refineries is included in the map for industrial representation. Chemical manufacturing facilities were selected from the Chemical Industries Association membership list and other industry research [21]. Oil refineries, although considered a separate industry (SIC 19), are included in the point map as they are featured in the Carbon Trust 2012 report on energy efficiency, and this information may prove useful to policy makers [22].

2.2.3. Analysis of the food and beverage sector

Disregarding energy for transportation, the largest source of waste heat in the food and beverage industry is assumed to come from heating, pasteurisation and refrigeration. A comprehensive map of all farms, abattoirs and food production sites was beyond scope of the project, as the list of UK dairies alone numbers almost 9,000 [23]. Thus, a waste heat map layer was created using data from large commercial breweries (SIC 11.05) and large dairy treatment centres (SIC 10.5), as both use pasteurisation and refrigeration processes. Only the fourteen largest brewing companies have been included in this study. A map of small, independent brewers has been compiled by an independent group, which could be useful in further industrial analysis into their heat recovery potential [24]. The three largest dairy producers in the UK were contacted with a single response offering a tour, but no quantitative data. All sites have been added to a point map.

2.2.4. Analysis of the minerals sector

The ceramics and cement industries were the focus of analysis in the mineral sector. Facilities included were those listed as a member of the British Ceramics Confederation and cement plants listed under the Mineral Products Association [25]. Each of the facilities belonging to the members of these associations are included in the point map.

2.2.5. Analysis of the vehicles sector

Data from the Society of Motor Manufacturers & Traders annual industrial report were used to provide vehicle data for active UK manufacturing sites (SIC 29) [26]. Active train manufacturing companies (SIC 30.2) were analysed. No responses were received from any automotive or train manufacturing company contacted and so the decision was taken not to contact any aircraft or ship manufacturers (SIC 30 exc. 30.2) as they are mainly contracted by the Ministry of Defence and deemed unlikely to disclose any information.

2.2.6. Analysis of the iron and steel sector

Iron and steel manufacturers were identified based on industry research. There are very few iron or steel works still operating in the UK, so this data was compiled ona case by case basis with facilities identified from internet searches.

2.2.7. Analysis of carbon dioxide emissions as an alternate proxy for waste heat

As carbon dioxide is released with the combustion of organic fuel, it can be used to provide an alternate method for approximating waste heat in Local Authority areas [27]. There are many potential sources of carbon dioxide that cannot be linked to waste heat. Therefore, only carbon dioxide emissions from non-domestic sources were considered in this study. The amount and distribution of carbon dioxide emissions in the UK are collected from the European Pollutant Release and Transfer Register (E-PRTR) [28]. These data provide the quantity and source of carbon dioxide emissions, allowing the sources that would not be suitable for waste heat reuse to be removed from the dataset.

3. Waste heat distribution and recovery potential

The total waste-heat resource in the UK was estimated to be 391,000 GWh. Findings have shown that although much of this heat can be recovered, some is either irreclaimable (such as heat produced by the welding of car bodies) or already being reclaimed (such as in the calcination preheating in cement production facilities).The following section details the distribution of waste heat opportunities in the UK and outlines the potential for waste heat recovery or reuse within each sector. The final sub-sections detail the demand for heating from natural gas and the required heat quality.

3.1. Total waste heat

Of the estimated 391,000 GWh of waste heat, around 46,000 GWh is emitted from industry. Waste heat from electricity generation is approximated to be 345,000 GWh. Distribution of total waste heat is focused mainly in the centre of the UK, in the Midlands and the North East as shown in Figure 2.

The majority of waste heat is produced by the electricity generation sector, with the food and beverage, chemical and mineral sectors all contributing large amounts. Metal processing and vehicle manufacture are estimated to contribute a smaller percentage of waste heat as outlined in Figure 3.

3.2. Electricity generation

Most waste heat in the UK is located centrally in Yorkshire and the Midlands with other localised high generation regions in other areas of the country as shown in Figure 4a. The total estimated waste-heat from electricity generation

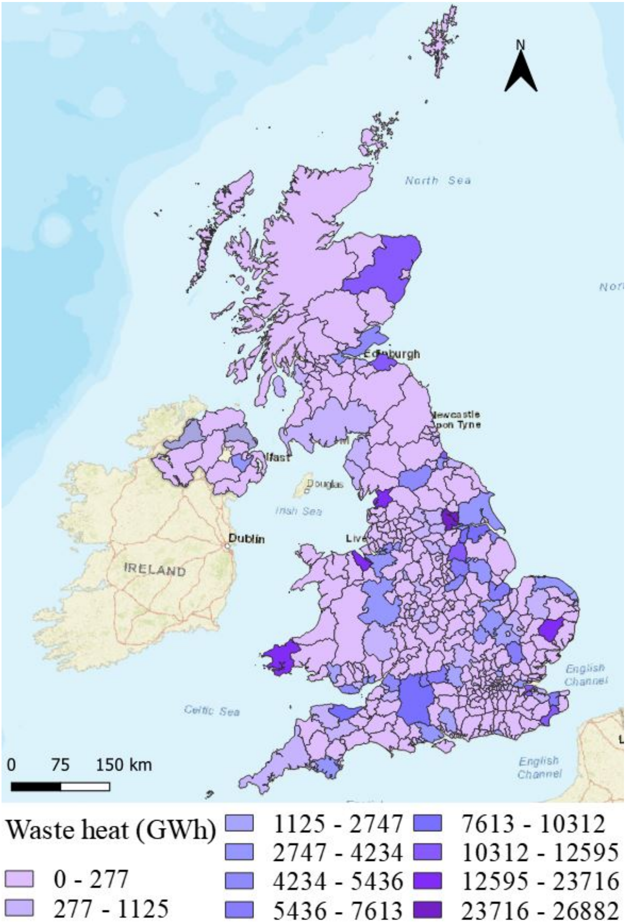


Figure 2: Distribution of estimated total waste heat in the UK by Local Authority area.

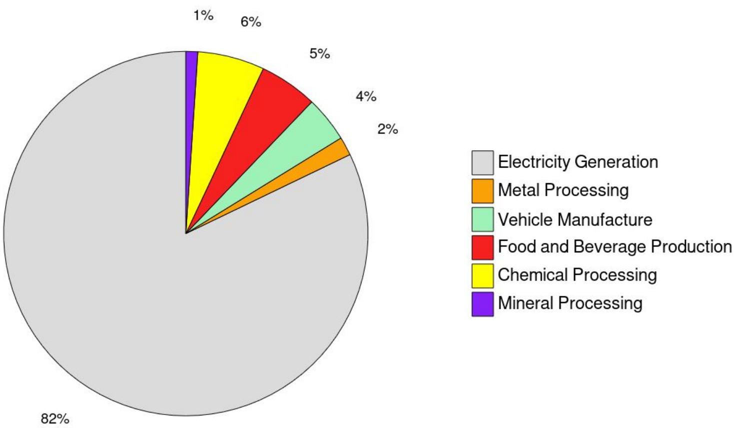
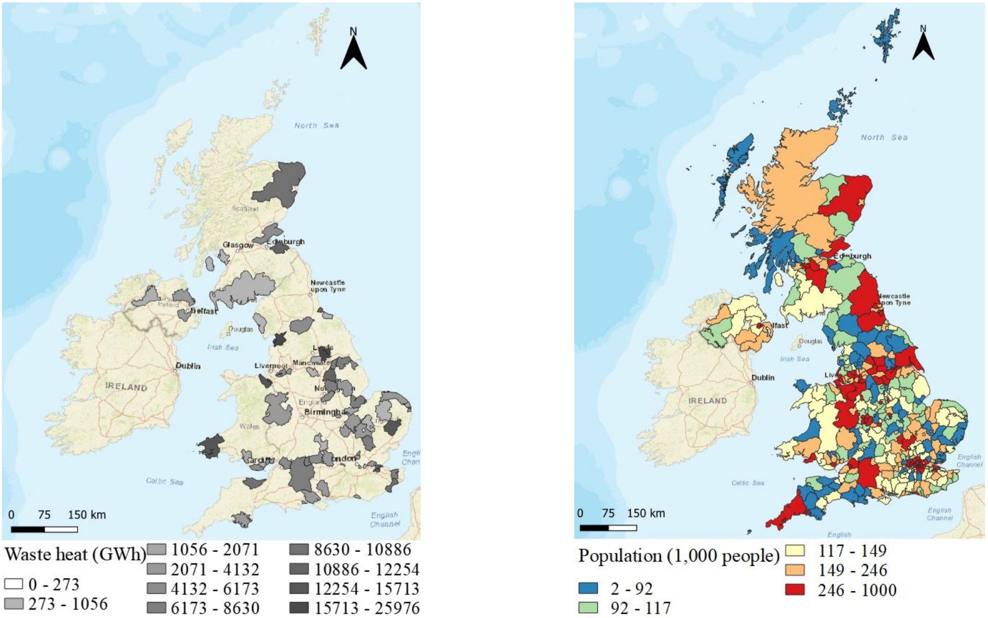


Figure 3: Distribution of estimated waste heat by sector.

was 345,000 GWh. Areas of high waste heat occur where there is a high concentration of power stations, especially those that are operating continuously or with a high load factor.

There are multiple factors that may affect the location of a power station, such as access to fuel and a suitable heat sink. Historically, the building of power stations resulted in an increase in population density caused by an influx of workers. This may explain the rough correlation between waste heat from electricity generation and population density, seen in Figures 4a and 4b. Data for the population distribution comes from the Office for National Statistics [29]. However, the location of different types of power stations will be dependent on different factors. For example, natural gas power stations are found on the coast, close to gas pipelines, which may explain the high waste heat approximations in Aberdeenshire and South Wales. Detailed analysis of the location of each type of power station is beyond the scope of this report. Each type of electricity generation plant has unique characteristics. The findings regarding the waste heat from each type of facility are discussed below.



(a) (b)

Figure 4: a)Distribution of estimated waste heat from electricity generation in the UK by Local Authority area. b) Population distribution in the UK by Local Authority area.

3.2.1. Natural gas

As of summer 2019, there were 61 natural gas power stations in the UK. This includes the categories Gas, Gas Oil, Gas Oil/Kerosene and CCGT. CCGT power stations make up 38 of these power stations and have a thermal efficiency of 49%, with an installed capacity ranging from 50 to 2,199 MW [19]. CCGT power stations have a power load factor of 42.7%, indicating that they are operating a large percentage of the time when compared with other power stations, where all except nuclear have lower load factors. Therefore, CCGT power stations contribute approximately 120,000 GWh to total waste heat (Table 1). For the purpose of this study, all natural gas power stations were assumed to have the same efficiency and load factor.

3.2.2. Nuclear power

All except one nuclear power station in the UK are Advanced Gas-Cooled Reactors (AGR). The AGR has an efficiency of approximately 40% and a power load factor of 72.3% indicating that there is a large resource of waste, as they are operating the majority of the time [19]. The UK will remain dependent on nuclear energy for part of the energy supply as the transition to renewables is made. Although the current nuclear fleet is to be decommissioned, these facilities may be replaced by small modular reactors offering a potential continuation of the waste heat source.

3.2.3. Coal

There were seven coal-fired power stations still in use in the UK as of summer 2019. An approximate thermal efficiency for a coal plant is 34% with a load factor of 14.2% in 2018 [19]. Due to their inefficiency and high installed capacity, coal fired power stations produce a large amount of waste heat when in use. However, a low load factor means the power stations are only operating a small fraction of the time. There is also a continuous push to remove coal from the energy network in the UK, planned to be achieved by 2025. Therefore using waste heat from coal fired power. stations is not a sustainable option.

3.2.4. Solar

There are 18 solar power stations in the UK recorded by BEIS, with an average installed capacity of 36.9 MW and approximate efficiency of 15% [30]. Due to their dependence on the weather, solar power stations have a low load factor of 11.3%. This limits the potential of solar waste heat, especially as solar waste heat availability will be lowest in the winter, when it is required most. Combining a photovoltaic cell with a metal absorber can create a photovoltaic thermal (PVT) collector [31]. These hybrid collectors could be utilised to increase the efficiency of solar panels by collecting heat simultaneously. However, the UK has a very small PVT market and the 10-100 systems installed each year are for domestic use [30]. Therefore, it is unlikely that PVT technology will be utilised in waste-heat recovery in the near future, although the technology is available.

3.2.5. Biomass

Biomass power stations are approximately 36% efficient [32], but this can depend on the type of fuel, its energy content and, the generation method. In biomass pyrolysis, thermal decomposition starts at 350-550°C and rises to 700-800°C in the absence of oxygen [33]. Therefore, there is a large reserve of waste heat available from biomass power stations, although the amount of waste heat is difficult to quantify on a large scale because of the variation in types of biofuel and methods of energy extraction from them. There are ten biomass power stations identified in this report, with an average installed capacity of around 210 MW.

3.2.6. Energy from Waste (EfW)

Pre-treated non-recyclable waste is burned at high temperatures under controlled conditions [34]. Incineration plants are designed to ensure that flue gases reach a minimum temperature of 850°C for 2 seconds [35], which makes them a high-grade heat resource. According to DEFRA, EfW power stations reach efficiencies of 15 – 27%, but that most modern facilities have an approximate efficiency of 25% [36]. A load factor of 21.8% suggests that EfW facilities are only used when necessary, however as they are more sustainable than fossil-fuel powered facilities they are more likely to be able to supply waste heat, if not continuously, for a long period of time.

3.2.7. Oil

Power stations dependent on oil include OCGT and diesel. They are grouped and assumed to have the same efficiency and load factor as natural gas-powered power stations, as both depend on fossil fuel. The 8 diesel power stations are situated on Scottish islands, where without a small local diesel generator there would be blackouts. They are small and produce very little waste heat.

3.2.8. Waste heat from electricity generation

Information provided by DUKES categorises power stations under the titles given in the first column of Table 1. For the purpose of this study, power station types are grouped together to simplify calculation. Coal and coal/oil are given the same efficiency and load factor as coal power stations. Gas, gas oil, gas oil/kerosene and CCGT are grouped and given the same efficiency. OCGT and diesel are grouped as OCGT power stations. Load factors are taken from DUKES, plant loads, demand and efficiency are shown in Table 1 [19].

Table 1
Electricity generation waste heat. Data is taken from [19] unless otherwise stated.

Power Station Type	Number	Average Installed Capacity (MW)	Efficiency (%)	Load Factor (%)	Estimated Waste Heat (GWh)
Coal	6	1,932.00	34.1	14.2	30,000
Coal/Oil	1	560.00	34.1	14.2	
Gas	8	102.69	48.9	21.8	120,000
Gas Oil	14	73.43	48.9	21.8	
Gas Oil / Kerosene	1	140.00	48.9	21.8	
CCGT	38	793.18	48.9	42.7	
OCGT	1	32.30	48.9	21.8	20
Diesel	8	17.61	48.9	21.8	
Biomass	11	211.03	36.0 [31]	21.8	29,000
Waste	11	35.86	25.0 [35]	21.8	
Nuclear	8	1170.13	39.8	72.3	91,000
Solar	17	36.09	1.05 [37]	11.3	76,000

3.2.9. *An example calculation: Electricity generation from coal.*

In 2018 Elexon reported an average power consumption from all coal power stations of 1,756 MW. Therefore, the total electricity generated over the 8,760 hours in the year was 15,385 GWh. Using the BEIS average coal power station efficiency figure, 34.1%, the total energy of coal consumed to produce this electricity was 45,251 GWh. Therefore, the heat wasted from coal power stations in the UK was 29,866 GWh. This energy was then distributed between the coal power stations weighted by their installed capacity as reported by DUKES in Table 5.11. For example, the Fiddler's Ferry power station in Cheshire has an installed capacity of 1,961 MW and therefore has a weighting of 1,961 MW / 11,592 MW, where 11,592 MW is the sum of the total installed capacities of all coal power stations in the UK. Therefore, Fiddler's Ferry is estimated to produce 29,866 GWh * (1,961 MW / 11,592 MW) = 5,052 GWh of waste heat.

3.3. Chemical

The chemicals industry is the second largest waste heat resource in the UK with an estimated 15,200 GWh of waste heat. Figure 5 demonstrates the spatial distribution of waste heat from the UK chemical sector. Chemical facilities tend to be based near ports, facilitating easy imports and exports, and steeped in a historical industrial presence. As they are often based in large clusters away from domestic settlements, use for district heating networks could be limited. However, internal use within companies or around industrial sites could have some potential. No indication of seasonal variation has been found in the chemicals sector.

The manufacture of chemicals is an exceptionally broad industry with heating required for a distillation, curing, boiling, drying, cooling, transportation and cold storage [22]. Sterilisation and pasteurisation are also widely employed for products that are used and consumed by humans. The heating and cooling processes used by each company and heat recovery methods currently employed could not be found due to commercial confidentiality.

The 2012 Carbon Trust report on the chemicals sector includes simple energy saving initiatives such as keeping doors closed and insulating warehouses, tanks and pipes. This implies that energy efficiency considerations were still in their infancy in the sector. However, anecdotal information suggests that the industry is making improvements in heat retention and recovery [38].

The chemical industry is a prime candidate for Refrigeration Heat Recovery (RHR) systems. Products with a high volume of liquids and solids account for 85% of the total process energy consumption in the refrigeration of the product [39]. Thus, a large proportion of the products manufactured by the industry would have large potential energy savings if RHR technologies were employed.

Figure 5: Distribution of estimated waste heat from the chemical industry by Local Authority area.

3.4. Food and Beverage

A total waste heat reserve of 14,700 GWh was calculated for food and beverage processing facilities. The heat distribution is displayed in Figure 6. Breweries and dairies are analysed in detail below.

3.4.1. Breweries

A non-automated response rate of 14% to enquiries of commercial breweries about quantitative energy consumption and current heat recovery techniques gave the useful insight that heat recovery from refrigeration or cooling plants is never used in the responding companies [40]. Independent breweries show a fairly even but patchy distribution across the country. These breweries are often attached to a public house. Thus, there is potential for waste heat recovery and use within the brewery-pub site. Due to the low grade of heat produced there is limited potential outside this setting. Large commercial breweries are located in cities or suburban communities.

With the current boom in the number of small, independent breweries and the progression of many to large commercial businesses, the application of heat recovery and RHR systems in the brewing industry would appear to be ideal for waste heat capture.

Brewing consists of four main stages before pasteurisation. Mashing involves grains and water heated to 67°C for 2 hours to produce the wort for boiling and fermenting [41]. Just before the wort is removed from the vessel it is heated to 75°C to deactivate the enzymes and stop the mashing process. The wort is then boiled at 100°C for an hour with hops to infuse flavours into the beer. The beer is then cooled in a heat exchanger to 6-25°C for fermentation which lasts 5-6 days. The beer is then aged between -1-10°C for a week before it is pasteurised at 75°C for 30s during 'flash sterilisation' and sent to market. Measures such as heat recovery from the heat exchanger for wort pre-heating and other heat integration techniques could save 25% of the energy required for the brewing process [42]. By considering

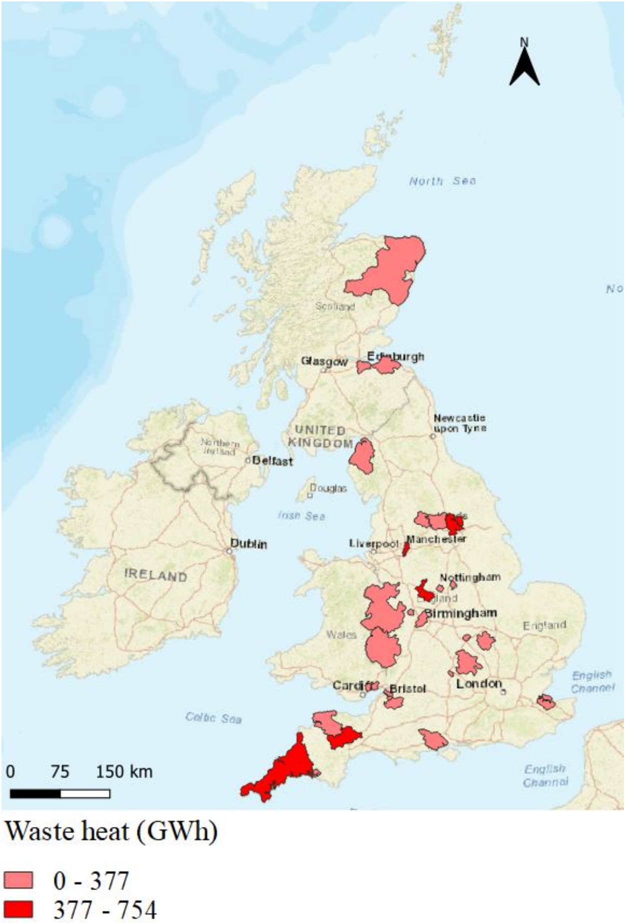


Figure 6: Distribution of estimated waste heat from the UK food & beverage sector by Local Authority area.

the spent grain discarded at the end of the brewing process or employing methods such as UV pasteurisation further energy reductions can be achieved [43].

3.4.2. Dairies

The UK produced 14,713 million litres of milk in 2017/18, almost all of which are subjected to pasteurisation and refrigeration [44]. The studied sites use various pasteurisation methods, the most common being high temperature short time pasteurisation, which occurs at 71°C for 15 seconds, and low temperature long time pasteurisation, which occurs at 63°C for 30 minutes. Both produce significant waste heat which can be captured through thin plate heat exchangers as the milk is processed. Milk is refrigerated at 3°C [45].

Use of RHR in pasteurisation was first found to be economically viable in a study from New Zealand conducted in 1987 [46]. Research and the commercial responses in this report have given little indication that refrigeration waste heat is used for anything other than defrosting the circuitry of the refrigeration unit. Dairies are making steps towards environmentalism, as seen with the biomass combined heat and power (CHP) plant at Arla's Aylesbury plant. Heat exchangers and dairies are often located rurally, away from densely populated areas. This makes the use of waste heat for district heating schemes questionable, however use within farming and other industry is plausible.

3.5. Mineral

Waste heat from the mineral sector is distributed across the middle of the UK, mainly in the Midlands, the North East and parts of the South as shown in Figure 7. These centralised locations are strategic for reducing transportation costs of the heavy cement. Historically, ceramics works are based in Stoke on Trent, therefore it stands to reason that there would be a high concentration of waste heat in this area. The total waste heat was estimated to be 10,400 GWh.

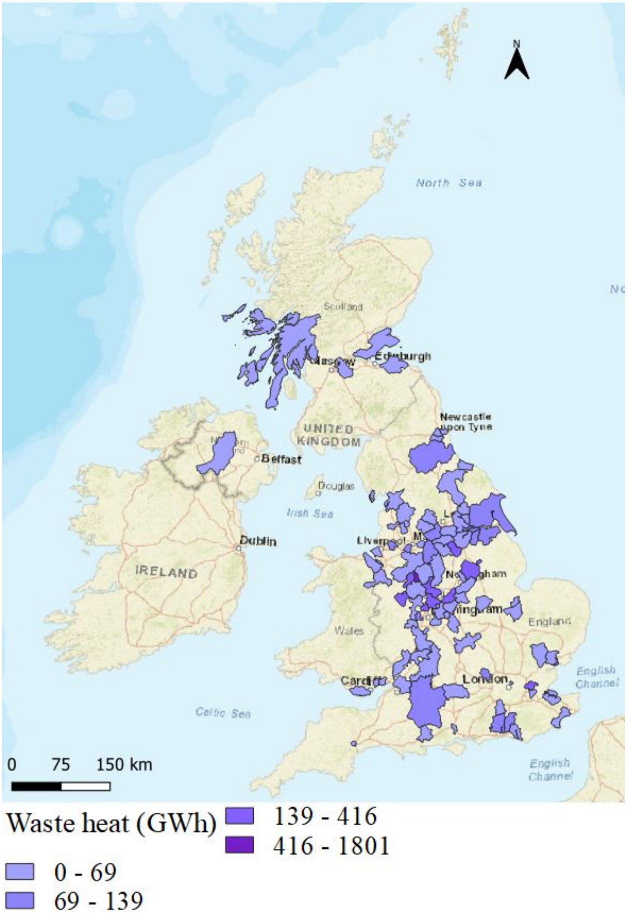


Figure 7: Distribution of estimated waste heat from the UK minerals sector by Local Authority area.

3.5.1. Cement

Responses to enquiries from industry members helped create a picture of the reuse of waste heat in a cement production facility. Cement is the basic ingredient of concrete and is a binder used in construction, where it is often lime or calcium silicate based [47]. A large amount of the cement used in the UK is manufactured locally, as it is expensive to import because of its density and high demand. In the case of Portland cement, there are 12 manufacturing and two grinding and blending plants in the UK that produce around ten million tonnes of Portland cement each year, about 90% of the cement sold in the UK [48]. The temperature reached in the cement kiln can be up to 1450°C [49]. To minimise energy waste from cement manufacturing, the waste heat from the cement kiln is fed back into an earlier stage through a preheating system. An example is given by Hanson Cement, where waste heat is recycled into the beginning of the process, where it is used in the calcination of the limestone [50]. On exit from the cement kiln, cement clinker is placed over a cooling grate and the high-grade waste heat is recycled into the coal mill to dry incoming coal. The majority of heat is lost in the kiln through the flue gases. The clinker exiting the kiln can be cooled in a grate cooler with cool air. The hot air is then used as a secondary air entering the furnace, reducing the energy losses.

The few replies received from members of this sector imply that heat reuse technologies are already implemented during cement making. Therefore, there may not be much room for development in this sector, particularly in terms of district heating schemes as there may not be enough waste heat to justify investment. Heat is likely to be of a high grade but available for a short period of time.

3.5.2. Ceramics

The ceramics industry includes the manufacture of brick, aggregates and pottery. The response rate was greater here than in other areas of enquiry at 9%. Some companies provided technical information of the temperatures involved in their manufacturing processes. Both Saint-Gobain Abrasive and Furlong Mills gave information on their gas and electricity usage but did not detail existing heat reuse processes. Although the responses were helpful, the low response rate means that the information provided was of little use, as it is anecdotal and therefore cannot be used to create a complete picture of the industry. During the manufacture of bricks, temperatures differ according to whether the bricks are made from clay or shale, but final drying takes place at around 200°C, dehydration at around 150 - 1000°C, oxidation from 500 - 1000°C and vitrification from 850 - 1300°C [51]. Therefore, further research needs to be done on ceramics manufacture in the UK to assess its potential for use in heat reuse schemes. The ceramics factories are clustered in the Midlands, such as Stoke-on-Trent, and are typically located near areas of high population density.

3.6. Vehicles

Automotive manufacture occurs in the historic manufacturing centres of the country and is estimated to generate 4,200 GWh of waste heat. Birmingham, Warwick and the North-East all have high densities of vehicle manufacture facilities and this can be seen in Figure 8.

As with the majority of UK industry, the domestic production of vehicles is gradually decreasing. This, in conjunction with the extreme difficulty of extracting sufficient quantity and grade of heat from industrial processes leads to a sparse prospect regarding heat reclamation from vehicle plants in the UK. The primary energy demand for the manufacture of a medium-sized passenger car is estimated to be 69 GJ (including mining and transport) [52]. 50% of the energy demand of assembly is in the painting process which requires the paint to be heated before it can be sprayed onto the vehicle body. The temperatures required for commercial spray painting are difficult to find if not redacted completely. However, there is theoretically some potential for waste heat recovery [53].

An estimated 288 MJ is required to weld each car. There is little available research or outlook for heat recovery from welding processes [52].

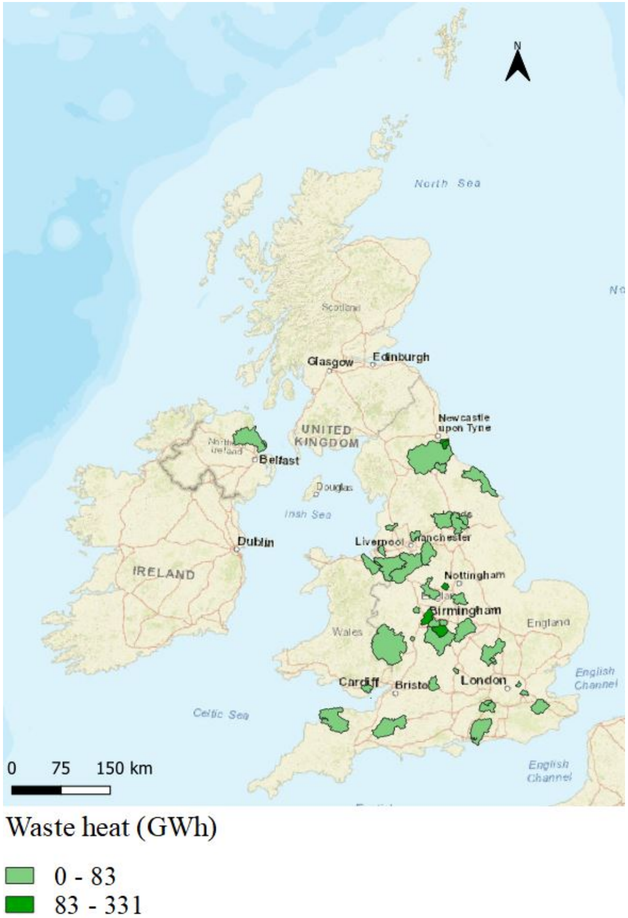


Figure 8: Distribution of estimated waste heat from the UK vehicle sector by Local Authority area.

3.7. Iron and steel

Iron and steel manufacturing processes require a large amount of energy because a blast furnace is required. The high temperatures of the furnace lead to an estimated 2,800 GWh of waste heat from this sector in the UK. There are few large-medium sized iron and steel works operating in the UK, the majority are in densely populated areas, such as South Wales and North East England as illustrated by Figure 9.

The hot blast temperature of the blast furnace can vary from 900-1300°C but can reach 2300°C depending on the design and condition of the stove [54]. It is possible for waste heat to be extracted from the flue gases of the blast furnace and because of the high temperatures, the waste heat is likely to be high grade. Molten slag is exhausted with a high temperature of about 1450-1550°C and therefore is also a potential energy resource. More investigation is required to assess whether the heat extracted from an iron or steel manufacturing facility could be of a grade and quantity high enough to use in a district heating scheme. This is likely the case, however due to the declining nature of the iron and steel industry in the UK, it is unlikely it will be of use in future district heating schemes.

Figure 9: Distribution of estimated waste heat from the UK iron & steel sector by Local Authority area.

3.8. Carbon dioxide emissions

This study found that the majority of carbon dioxide emissions arise from the energy sector, essentially as a by-product of the combustion of organic fuel. Other major emitters of carbon dioxide are chemical processing, waste and waste water management, mineral processing, paper and wood production, food and beverage processing and production and processing of metals. The weighting of carbon dioxide emissions is similar to the weighting of waste heat distribution estimate across industry. This can be seen in Figure 10. Data on carbon dioxide emissions were provided by the E-PRTR, utilising a bottom-up approach [52]

Figure 11 demonstrates that the concentration of carbon dioxide emissions is greatest in the North East, the Midlands, South Eastern Scotland and Northern Ireland. The areas displaying the lowest emissions are Cornwall, Devon, Dorset, East Anglia and the Highlands. As expected, the areas with the greatest emissions are areas with a higher density of industry. Rural areas, such as Dorset, Somerset and the Highlands, have either no or very low emissions data from industry. When used to approximate waste heat distribution, the distribution of carbon dioxide emissions suggests that areas in the Midlands, the North East and South East Wales would be most appropriate for the implementation of district heating schemes. This is a similar distribution to that seen in Figure 4b.

3.9. Natural gas demand

If households are to become more dependent on district heating schemes for their heating, a balance between demand and supply of waste heat is necessary. There is a large variation in domestic gas demand between summer and winter, which correlates with smaller variations in industrial gas demand and demand from the electricity generation sector over the same timescale. Therefore, increasing the dependency of households on waste heat from both the

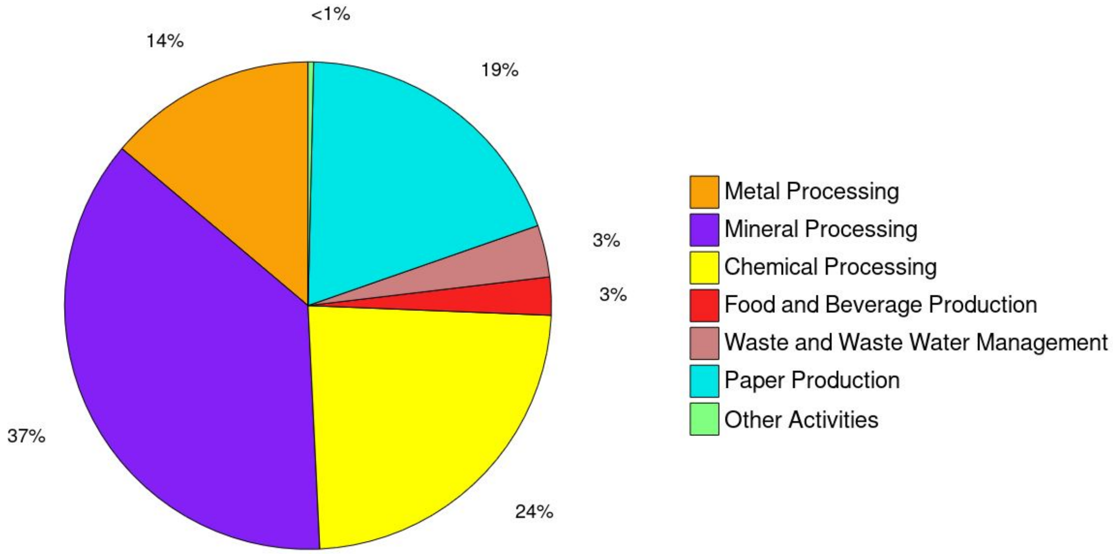


Figure 10: Distribution of UK Carbon dioxide emissions across industrial sectors.

industrial and electricity generation sectors is a viable option because an increase in demand for heat correlates with an increase in supply.

3.10. Heat grade

The grade of waste heat is dependent on its temperature, with higher temperature equalling higher grade [55]. In general, the the higher grade waste heat is more useful [56]. Recovered heat of 70-80°C is useful in district heating schemes, as domestic and non-domestic buildings require a flow in this temperature range so that no material changes to building fabric are required. Waste heat in the range of 40-70°C is more suitable for modern buildings with suitable insulation and underfloor heating. For waste heat of this grade to be supplied to customers without these building modifications, the heat must be elevated to a higher temperature using a gas/biomass boiler or a heat pump. This added cost often prevents this use of waste heat. Low grade heat of 30°C or less is most useful in the winter and when its supply is constant, however a heat pump is needed.

3.11. Limitations and accuracy

Data for this study were taken directly from BEIS and Elexon and both deal with granular data taken from individual energy transactions. These data are taken to be accurate and complete. The assumptions made for each industry have been formulated from available data and studies concerned with each industry and are outlined below. These assumptions are likely to form limitations in the accuracy of the work. Carbon dioxide distribution data are similar to waste heat distribution data, qualifying that despite the assumptions made the waste heat distribution is relatively accurate.

- Electricity generation: Elexon gives energy transfer data accurate to half-hourly periods for each power station type. The efficiencies have come, where possible from BEIS, or other reputable sources. These high resolution sources are thought to provide a high level of confidence in the identified distribution.
- Chemicals industry: The Carbon Trust report details that half of the chemical industry is concentrated in four discrete areas (those represented on the map) and the rest is widely dispersed around the UK. Therefore, there will be a greater potential for waste heat recovery than outlined in this report. However, the wide distribution of the rest of the industry could reduce the practical potential for heat recovery.
- Food & Beverage: The number of individual abattoirs, bakeries, vintners and food processing plants is colossal. The decision was taken to prioritise the grade of available waste heat over the quantity of sites. Therefore, the spatial representation displayed on the map is thought to give a fair estimation of the overall distribution, as food

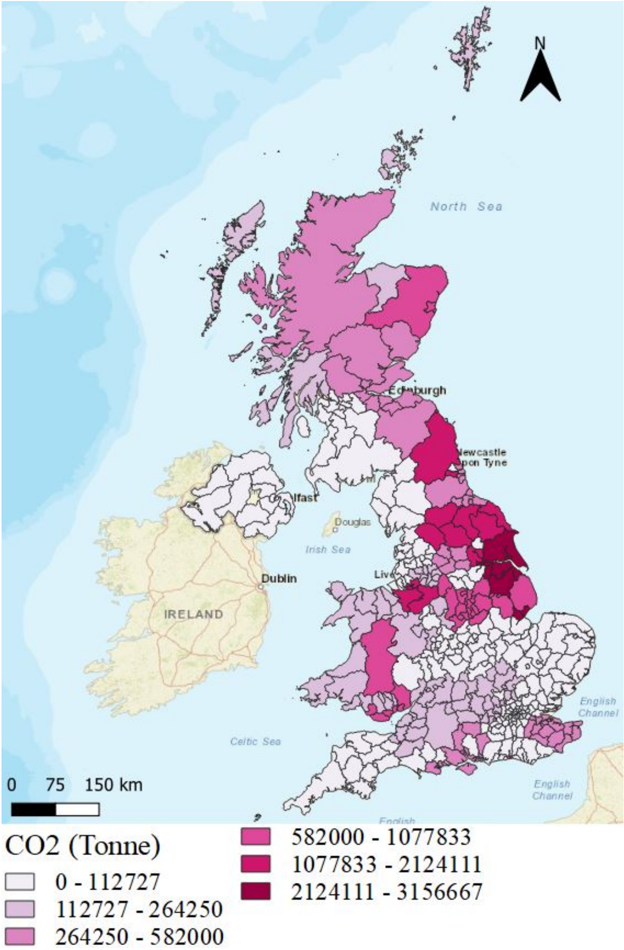


Figure 11: Distribution of carbon dioxide emissions in the UK by Local Authority area.

processing plants are likely to be located near to regions with a higher intensity of agriculture or to ports thus concentrating the waste heat recovery potential.

- Minerals: Only sites listed under the British Ceramics Confederation and cement plants listed under the Mineral Products Association were investigated, and all listed sites were analysed. While excluding facilities not on these catalogues is likely to reduce the accuracy of heat recovery potential, it is likely that manufacturing plants not included on the lists are sufficiently small as to have a insignificant effect on overall distribution.
- Vehicles: The points included for the vehicle industry are believed to be comprehensive. However, this resource is likely to deplete over time as the UK ceases vehicle production.
- Iron & Steel: No comprehensive list of operational iron and steel works could be found; therefore they were selected based on broad industry research. It is therefore possible that facilities have been missed, this would reduce the accuracy of the heat recovery potential distribution.

4. Discussion

The above analysis demonstrates that there is a large, well-distributed resource of waste heat from non-domestic sources in the UK that has the potential to be utilised in heat recovery schemes such as district heating. It is clear that much of the waste heat identified in this study could be reused. The location of industry is approximately correlated with population density, which is expected as settlements are usually built in areas with good natural resources. Seasonal variation in waste heat and heat demand are correlated. Furthermore, making use of this resource would reduce carbon dioxide emissions, aiding in reaching the UK's target to be carbon neutral by 2050.

The novel presentation of waste heat potential by spatial distribution that provided here extends the work of Hammond et al. [9] and Brueckner et al. [10] in advancing the tools available to policy makers and private companies for implementing waste heat recovery strategies. Such tools must be used by these parties to reduce the amount of heating that is required for industrial and domestic processes and limit climate change. Our novel method for simply identifying the spatial distribution of waste heat should be used to aid global decarbonisation and compliment work into sources and uses of waste heat. For example: work from the heat network global collective [56] would be complimented by national waste heat maps to identify sources of waste heat for integration into district heating networks. As the energy consumption and industry efficiency figures will differ by country and over time, the method outlined in section 2 will need adaption to suit the data available, however as a strategy of achieving the overall goal of generating an informative tool, the method outlined in Figure 1 should be followed.

In the UK, total waste heat is focused in areas with a traditionally strong presence from industry and high population density, such as Yorkshire and the Humber as shown in Figure 12. These areas are well connected to power stations and close to roads for transportation. Proximity to facilities with large quantities of waste heat makes these areas appropriate for district heating schemes. They are often already well connected to industry, in particular the electricity generation, mineral and chemical production sectors.

Figure 14 details approximate population density across each region of the UK [57]. It can be seen that on average the areas with high population density are those with high proportions of waste heat and high CO2 emissions.

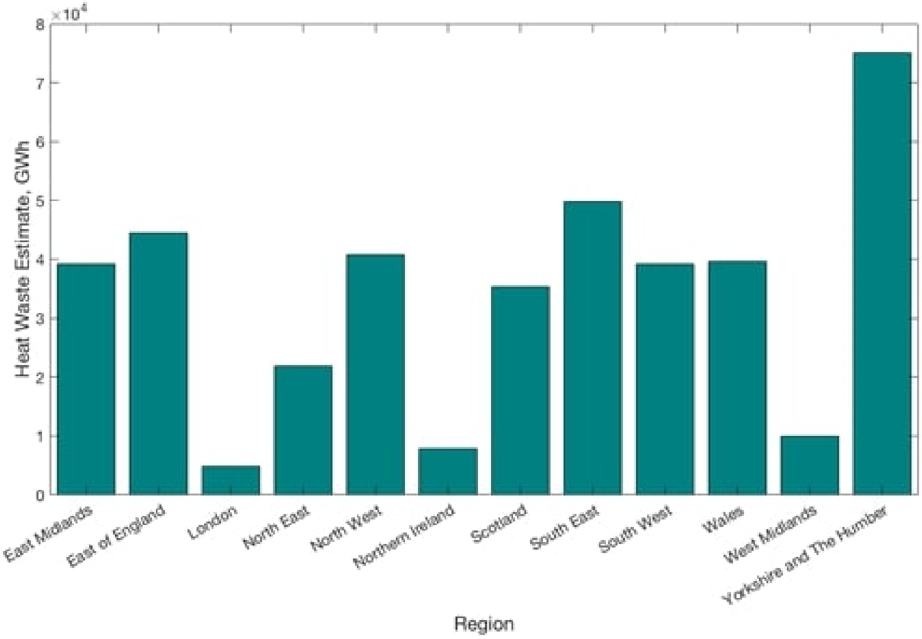


Figure 12: Regional distribution of estimated waste heat in the UK.

The electricity-generation sector accounts for the majority of waste heat and therefore should be the focus of any waste-heat recapture scheme. By analysing the point map shown in Figure 15, we see that the Local Authority areas containing one or more power stations are often those with higher waste heat. In particular, CCGT and nuclear power stations would be appropriate because of their high load factor. However, neither CCGT nor nuclear power are renewable technologies and consideration needs to be taken to assess whether long term investment into heat reuse technology for these types of power stations is appropriate. Although nuclear power itself does not release carbon dioxide, it is an extremely resource intensive technology and much carbon dioxide is released in the building and upkeep of a nuclear power station and the containment of nuclear waste. Research into waste heat capture from renewable technologies may be more appropriate and other, more permanent industries, such as the mineral and chemical sectors

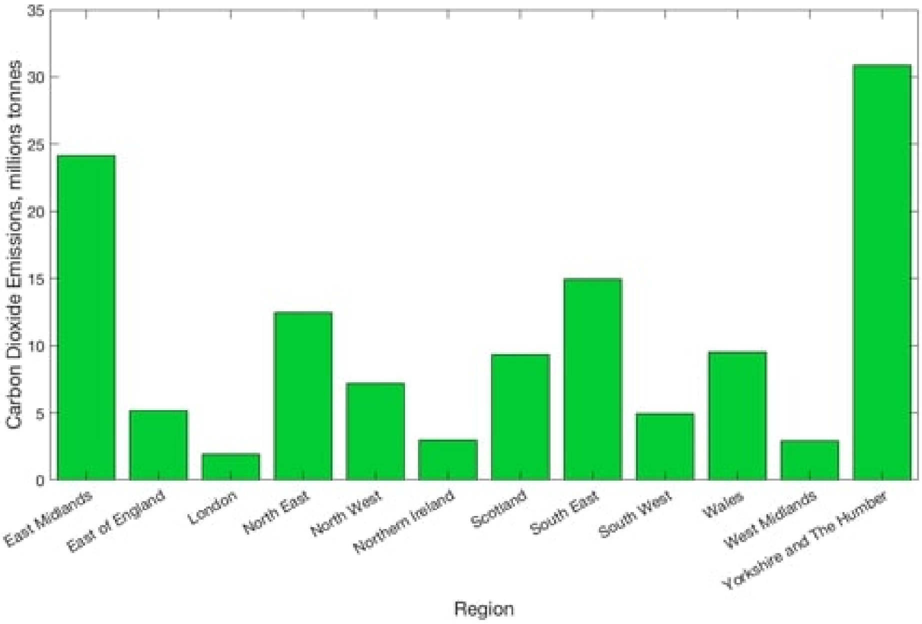


Figure 13: Geographical distribution of carbon dioxide emissions in the UK.

may be investigated, although they offer a lower quantity of waste-heat. In addition, most primary energy use in UK industrial processes relies on natural gas. If the UK is to meet its climate goals set for 2050 it must drastically reduce its reliance on fossil fuels throughout society. Therefore developing and establishing systems for, and mobilising large investments in, waste-heat reuse networks based on non-decarbonised industrial processes will delay the required fossil fuel reduction and create systems reliant on sources which, by necessity, need to be phased out as part of policy. Therefore the authors recommend careful consideration and planning when selecting an energy source for any heat reuse system.

The distribution of carbon dioxide emissions also provides some information about the distribution of waste heat, although its distribution is not perfectly matched to that of estimated waste heat as illustrated by Figure 13. A large proportion of carbon dioxide emissions come from Yorkshire and The Humber, the East Midlands and the South East. Similar to patterns seen in the distribution of estimated waste heat, these areas have a large amount of industry and high population densities. Regions such as Wales, the South West and the North West produce a small amount of carbon dioxide, but account for a larger proportion of the estimated waste heat.

Discrepancies between the distributions of waste heat and Carbon dioxide emissions can be accounted for by approximations and assumptions made when estimating waste heat per Local Authority area. Data on carbon dioxide emissions were provided by the E-PRTR, utilising a bottom-up approach [58], and so have the potential for a greater degree of accuracy. The combination of maps of estimated waste heat, carbon dioxide emissions and point map facility locations should therefore be used to provide a detailed picture of potential waste heat distribution within each Local Authority.

The main issue this study faced was an extremely low response rate to enquiry from industry. This was disappointing, as it changed the scope of the project and limited the accuracy of much of the information provided by the UK heat map. A much better picture of waste heat potential could have been provided had this information been available. However, this demonstrates the reluctance from industry to divulge what it perceives to be commercially sensitive information, despite the clear need for clarity on this subject for there to be progress in industrial decarbonisation. The nature of ventures such as district heating schemes depend on the collaboration of different industrial factions to provide the necessary amount of waste heat. Without sharing even basic information on available waste heat, heat reuse schemes cannot hope to be implemented.

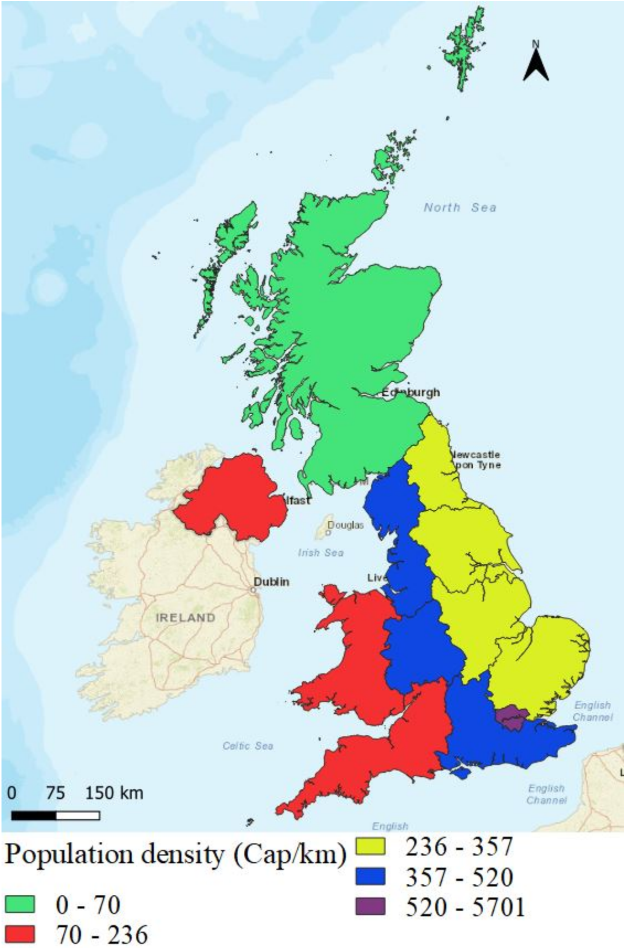


Figure 14: Average population density per region in the UK.

While it is assumed, and confirmed in a few cases, that there are many heat reuse technologies currently employed by companies at specific facilities, it is not known whether these are the most economic or sustainable options available and there is inevitably room for improvement. Therefore, if real progress is to be made in this area, it is paramount that the government encourage the sharing of information and expertise to develop the most suitable heat reuse scheme in each case. Although there are many heat networks already operating in the UK, the country is still massively dependent on natural gas for domestic heating. For heat networks to play a role in reducing and eventually eliminating the dependence on natural gas to reduce carbon dioxide emissions and create a greener future for energy and heating in the UK, more collaboration across industry will be needed.

5. Conclusions

As of 2019, only 450,000 homes, out of about 25 million, are heated from district heating networks. Many of these networks are fuelled by EfW or CHP systems.

This report has found that there is significant overlap between the spatial distribution of waste heat in the UK and the population demand for domestic heating. Certain regions, such as Yorkshire and The Humber and the East of England, show particularly high waste-heat potential, mainly due to the large, high capacity power stations in these areas. These are also areas with high population densities and therefore a great potential for heat reuse. The greatest potential for waste heat recovery is from CCGT and nuclear power stations, which could provide a near constant supply of heat due to the consistency in their operating profile as seen by their load factors. The potential for waste heat recovery

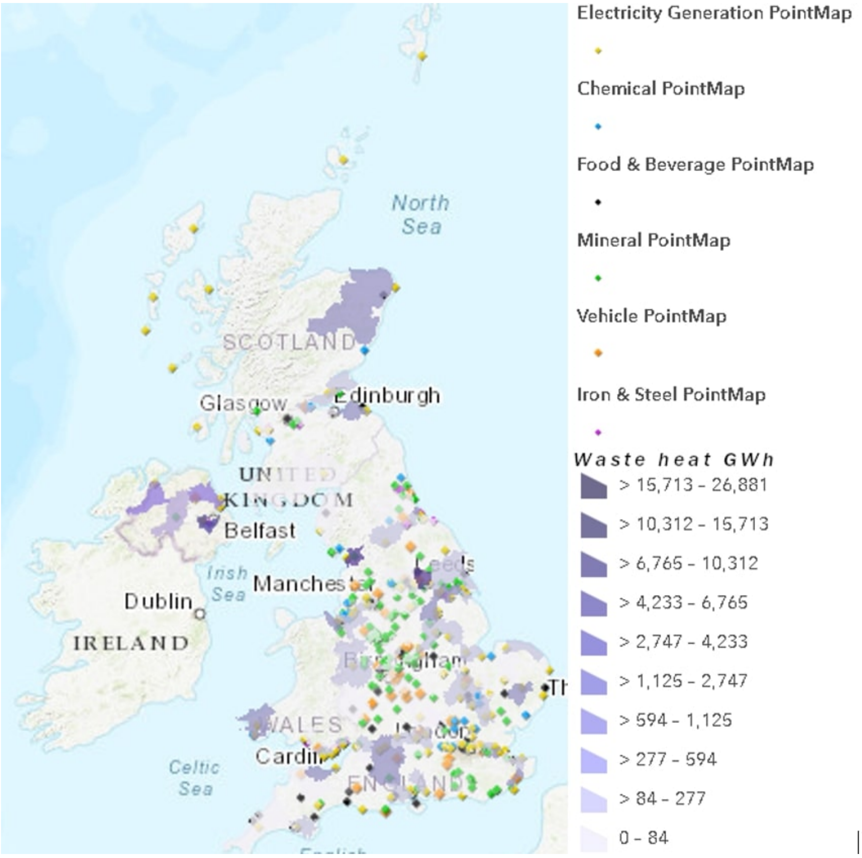


Figure 15: Point map data for all UK industrial sectors and the spatial distribution of the electricity generation sector. This figure is as presented by the authors on the MyGrid site [4]

from industry is smaller and less certain because usage patterns are less predictable and industry is largely concerned with profit. Financial incentives may be required to encourage t industry to adopt waste-heat reuse schemes. Certain industries, such as ceramic and mineral production, show a high availability of waste heat.

A novel methodology was used in this study, focusing primarily on the distribution of waste heat rather than a single quantitative value estimating its availability. We developed a tool and a framework for building a catalogue of sites from which policy makers, investors, and entrepreneurs can reduce the amount of waste heat in the UK and minimise its reliance on fossil fuels. The method outlined in figure 1 should form the basis of further local and international efforts to map waste heat.

This report identified a serious reluctance from industry to be involved in this study, potentially reflecting on the attitudes of industry towards collaborative heat reuse schemes. Poor response rate from industrial questionnaires limited the accuracy and scope of this work. These assumptions introduce uncertainties about the quantity and grade of heat available. However, analysis of carbon dioxide distribution confirms the distribution of waste heat at a basic level.

Significant change is necessary to lower carbon dioxide emissions in the UK, and industry must change its practises to reduce their emissions and consumption. If progress is to be made, UK industry must collaborate with studies such as this one to allow an increase in understanding of the problems faced and solutions available. However, the industries and electricity producers that provide the greatest availability of waste heat are also some of the less environmentally friendly industries in the UK and are all highly dependent on natural gas. We must ask: as industry is mainly powered by natural gas or gas-derived electricity, does the long-term sustainability of waste heat reuse technologies truly aid the move to a greener economy?

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