Heat recovery opportunities in UK industry

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Abstract

A database of the heat demand, and surplus heat available, at United Kingdom industrial sites involved in the European Union Emissions Trading System, was used to estimate the technical potential of various heat recovery technologies. The options considered were recovery for use on-site, using heat exchangers; upgrading the heat to a higher temperature, using heat pumps; conversion of the heat energy to fulfill a chilling demand, using absorption chillers; conversion of the heat energy to electrical energy, using Rankine cycles; and transport of the heat to fulfill an off-site heat demand. A broad analysis of this type, which investigates a large number of sites, cannot accurately identify site level opportunities. However the analysis can provide an indicative assessment of the overall potential for different technologies. The greatest potential for reusing this surplus heat was found to be recovery at low temperatures, utilising heat exchangers; and in conversion to electricity, mostly using organic Rankine cycle technology. Both these technologies exist in commercial applications, but are not well established, support for their development and installation could increase their use. The overall surplus heat that was technically recoverable using a combination of these technologies was estimated at 52PJ/yr, saving $2.2\mathrm{MtCO_{2e}/yr}$ in comparison to supplying the energy outputs in a conventional manner. It is thought that a network and market for trading in heat and the wider use of district heating systems could open considerable potential for exporting heat from industrial sites to other users.

Keywords: Heat recovery, industry, manufacturing, United Kingdom, waste heat, surplus heat.

Highlights:

- Heat recovery opportunities from UK industry were evaluated.
- Surplus heat availability was based on previous work.
- Various technologies to utilise the recovered heat were examined.
- Greatest potential shown for heat use on-site and its conversion to electricity.
- Transportation of heat shows potential, but will require the existence of networks.

NONMENCLATURE

Abbreviation

EU ETS	European Union Emissions Trading System
NAP	National Allocation Plan
CHP	Combined Heat and Power
CRC	Carbon Reduction Commitment
CCAs	Climate Change Agreements
GHG	Greenhouse Gas
COP	Coefficient of performance
ORC	Organic Rankine Cycle

Symbols

η	Energy efficiency
T	Temperature [K]

Subscript

0	Sink (environment)
P	Source (process)
D	Delivered

1. INTRODUCTION

The United Kingdom (UK) industrial sector is responsible for approximately 20% of the UK's final user energy demand [1], the vast majority of this energy is supplied through fossil fuels, either directly, or indirectly through electricity use. Emissions of greenhouse gases (GHGs), primarily carbon dioxide, are associated with the use of this fossil fuel, the reduction of these emissions is required to meet government targets, such as an 80% reduction in emissions by 2050, on 1990 levels [2]. Such emissions can be reduced by either decreasing the energy demand or supplying the demand in a less carbon intensive way. For the companies that comprise the industrial sector the requirement to meet legislation designed to reduce energy demand and carbon emissions (such as the EU ETS, CRC and CCAs), alongside the increasing costs of energy [3], should represent strong drivers to reducing energy demand.

Heat is responsible for approximately 70% of final energy demand in UK industry [4]. All heating processes result in a surplus of heat energy at the end of the process [5]. This surplus heat source[1] can, in certain cases, be recovered and utilised to fulfill an existing energy demand. Using surplus heat in this manner would replace conventional energy sources, and so reduce both energy costs and associated emissions. Heat recovery is commonly practiced in manufacturing, especially in energy-intensive industries, although it is thought that considerable potential still exists. The UK Government's Office of Climate Change estimated annual surplus heat recovery potential in UK industry at 18TWh (65PJ) in 2008 [6]. McKenna and Norman [7] subsequently estimated the surplus heat that could technically be recovered from those sites in the European Union Emissions Trading System (EU ETS) as 36-71PJ/yr. An end use for the surplus heat was not specified. The assessment by McKenna and Norman [7] and that by the UK Government's Office of Climate Change [6] were both based on conservative estimates and considerable uncertainty.

The aim of the current paper was to identify a use for the technically recoverable surplus heat identified by McKenna and Norman [7]. The objectives adopted to achieve this aim were:

1. To determine the required characteristics of a surplus heat source for it to be utilised through each of the examined heat recovery technologies. Further to identify the required characteristics of a suitable demand.
2. To assess the potential for the identified surplus heat sources to be utilised by the examined technologies under two scenarios:
    a. All surplus heat sources were available for use by each of the technologies.
    b. The technology (or technologies) that was applied to each surplus heat source was chosen to maximise a desired saving (eg. GHG emissions).
3. To discuss the results within wider knowledge.

The technologies assessed for utilising surplus heat sources were:

- On-site heat recovery, to fulfill a lower temperature demand, through heat exchanger networks or similar.
- Upgrading the surplus heat for use at a higher temperature, using heat pumps.
- Conversion of surplus heat to chilling energy, using absorption heat pumps.
- Conversion of surplus heat to electricity, using Rankine cycles.
- The transportation of heat, to fulfill an offsite heat demand.

The choice of technologies was based on the previously successful adoption of such technologies in utilising surplus heat sources within industry, and the availability of relevant information to allow an analysis of the technology. Due to the

[1] Also commonly referred to as a waste heat source. The term surplus heat source is used throughout to avoid confusion.

uncertainties surrounding the estimation of surplus heat availability, and technology performance when assessing opportunities on a broad scale, the analysis was intended to provide an indicative estimation of the potential. The analysis would not be expected to be accurate at a site level, but was conducted to indicate the scale of opportunities for different technologies, and to provide a basis for further, more detailed, analysis.

2. METHODOLOGY

2.1 Dataset

The dataset used here was built on previous work [7]. Each site within the Phase II UK National Allocation Plan (NAP) of the EU ETS was classified into one of thirty-three subsectors. Information on the processes undertaken within these subsectors was used in conjunction with emissions or output data at the site level to estimate heat demand and the technically recoverable surplus heat. Heat demand was estimated in five temperature bands (less than 100°C, 100-500°C, 500-1000°C, 1000-1500°C and over 1500°C). For each site the temperature and magnitude of a single surplus heat source was estimated. Due to the uncertainties involved in estimating the surplus heat recoverable, a range was applied to the magnitude of each surplus heat source [7]. The methodology adopted in the current work differs slightly from that used previously [7]. Formerly only fuel use was assumed to contribute to heating demands, with the exception of subsectors where it was known the majority of heating was supplied by electricity (for example, in electric arc furnaces) [7]. In the current work a proportion of electricity demand at all sites was assigned to heating processes, this proportion was based on available data for the UK [4]. Any heat demand currently fulfilled by CHP plants was removed in the current work. As this demand was already met in an energy efficient manner, it was not felt appropriate to replace it with surplus heat. There were a total of 425 sites included in the analysis. The data used refers to the time period from 2000-2004 with the heat demand and surplus heat available based on the mean emissions recorded in these years (with the highest and lowest values removed). This assessment covered approximately 60% of total industry and 90% of energy-intensive industry energy demand [7]. Energy demand in UK industry since this period has reduced, due in part to the economic recession experienced in the UK. Energy demand fell by 20% between 2004 and 2010, with the majority of this drop occurring during 2008-2009 [8]. Some large users of energy ceased operations over this period, e.g., the Teesside integrated iron and steel works was mothballed in February 2010 [9]. However, the plant has since changed ownership [10], and the blast furnace was relit in April 2012 [11]. Additionally two of three UK aluminium smelters were closed, or their closure was planned [12, 13]. Likewise closures have occurred in the Cement and Pulp and Paper subsectors. The long-term future of these plants, and how much capacity other plants may change in response, is uncertain. The information presented here was unaltered from that over the 2000-2004 period.

2.2 On-site heat recovery

For each site in the analysis, if there was a heat demand in a temperature band below the temperature of the surplus heat source, then heat recovery was assumed to be able to occur. All or part of the surplus heat could be recovered in this manner, dependent on the size of the demand. The technically recoverable surplus heat source was identified by previous work [7], it was all assumed available to fulfill an energy demand with no further losses.

Sites that were classed separately in this analysis could exist at the same location. An example were integrated Iron and Steel sites, where different parts of the steel making process were classed as different sites, due to the large differences in temperature demands and surplus heat availability in different parts of the process. The use of heat from one of these

notional “sites” at another, which shares the same location, was classified as heat reuse on-site. Reusing heat at the same ”site” (rather than same location) was prioritised however. If heat demand in more than one temperature band could be supplied by the surplus heat source, the highest temperature demand was prioritised. This maximised the exergy efficiency of the heat transfer process. No limitations to the temperature of demands that could be met through heat recovery on-site were imposed. The temperatures of heat recovery can be seen in the results, and the effect of possible temperature limitations are discussed in section 4.1 below.

Heat recovery may take place by direct mixing of the surplus heat source with a suitable sink, or more commonly through the use of heat exchangers. The technology that would be used was not specified here, such decisions would require a site level analysis. There may also be some additional energy requirement for heat recovery, due to the use of pumps and control systems. However this would be small in comparison to the heat recovered [14] and was ignored in the present analysis for all technologies.

2.3 Heat pumps

For the current analysis it was assumed that heat pumps could be used to supply a heat demand in the lowest temperature band (less than 100°C) using a surplus heat source of less than 80°C. This was based on the performance of commercially available technology [15-17]. Heat pump performance is defined by the coefficient of performance (COP), which is the ratio of heat output to work input (normally electricity, and assumed to be so here). The maximum theoretical COP (Carnot COP) is defined by the temperatures of the heat source and the heat delivered [15]. The COP reached in practice is approximately 55% of the Carnot COP [15]. A simple expression for the COP of a heat pump can therefore be derived:

$$\mathrm{COP} = 0.55 \cdot \mathrm{COP}_{\mathrm{Carnot}} = 0.55 \cdot \frac{T_D + 5}{(T_D + 5) - (T_P - 5)} \quad (1)$$

T_D is the temperature of delivered heat and T_P the temperature of the heat source. The additional terms (±5K) are incorporated as the Carnot COP is calculated using the temperatures of the refrigerant in the heat pump. These extra terms represent the temperature difference required to induce heat transfer between the refrigerant and the environment.

2.4 Heat to chilling

Surplus heat can be used to drive an absorption chiller. Within UK manufacturing almost all the chilling requirement is within the Food and Drink and Chemicals subsectors [4]. For these subsectors the amount of chilling that could be provided using absorption chillers, with the identified surplus heat, was estimated. For surplus heat temperatures of 100-170°C a single effect chiller was assumed to be used, with a COP of 0.7 [18]. From 170-300°C a double effect unit could be used, with a COP of 1.0 [18]. In each case, an output of at least 350kW of chilling capacity was required [18].

2.5 Heat to electricity[2]

Surplus heat can be converted to electricity through a number of technologies. Organic Rankine cycles (ORCs) and traditional Rankine cycle technology have both been utilised successfully in industrial surplus heat to electricity applications [19, 20] and are considered here. Generally at higher temperatures (above 400°C) the traditional cycle is used, whilst at lower temperatures an organic fluid is required [5, 14, 19]. However other factors such as the composition and magnitude of

[2] This is often referred to as heat to power technology. The alternative term is avoided here, as power is also used to refer to an energy demand per unit of time.

the heat source influence at what temperature a given technology takes preference. There are instances of organic working fluids being used with a source temperature of approximately 500°C [5, 21]. In the current study whether water or an organic fluid would be used in the Rankine cycle was not specified. The expected efficiency of a technology only varied with the temperature of the surplus heat, it was independent of the specific technology used.

The theoretical efficiency of converting heat to electricity is defined by the Carnot efficiency (η_{Carnot}), which is dependent on the temperature of the heat source (T_P) and heat sink (T_0), such that [22]:

$$\eta_{Carnot} = 1 - \frac{T_0}{T_P} \qquad (2)$$

T_0 is normally defined by the environment and so is relatively constant (taken as 25°C here). Therefore the higher T_P (in this case the surplus heat temperature) the higher the possible efficiency of its conversion to electricity. Figure 1 shows the Carnot efficiency for converting heat to electricity at different source temperatures alongside the net efficiencies at different temperatures reported by four manufacturers of ORC systems [21, 23-25] and a typical efficiency of a steam Rankine cycle at 550°C [26]. A logarithmic curve was fit to this data to estimate the efficiency of a heat to electricity cycle at a given temperature.

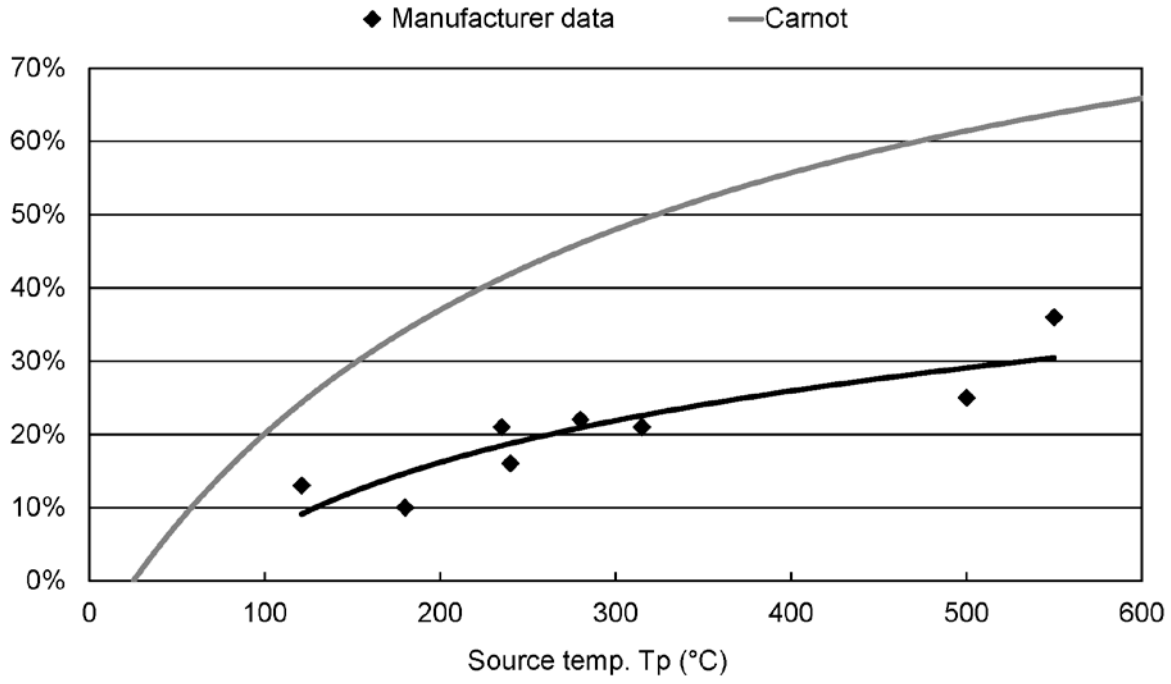

Figure 1 Theoretical (Carnot) and practical efficiencies of heat to electricity cycles, as temperature varies.

The minimum power output for a viable heat to electricity project was set at 0.5MW_e. This was based on information obtained from manufacturers of ORC systems [21, 24, 25]. This required output was combined with information on efficiency in order to define the required magnitude of the surplus heat supply at a given temperature. For the current study 100°C was adopted as the minimum required temperature for a heat to electricity application, based on a number of sources [5, 19, 21, 24, 25]. There was no maximum temperature imposed on the surplus heat that could be utilised to produce electricity. The maximum temperature at which standard equipment can be used is approximately 550°C [26]. If temperatures above this were utilised it was assumed that the temperature was lowered to 550°C, with air bleeding, and so the efficiency was limited by this temperature. It was not necessary to identify a demand for the produced electricity, it could be exported to the grid if it exceeded the site's demand.

2.6 Heat transportation

An assessment was made of the potential to transport surplus heat from one site to fill demand at another site included in the analysis. It was assumed that heat could be transported up to 40km [6], with a 10km limit most likely [27] . The efficiency of this heat transportation was assumed to be 25-75% (based on a range of reported values for different technologies [27]). The efficiency of heat transport could have been linked to transportation distance and temperature but, given the considerable unknowns in how heat transportation would occur, this wide efficiency range was adopted in order to indicate the uncertainties involved.

Like recovery on-site, surplus heat was used to fulfill a heat demand in a lower temperature band when transported to another site. No restriction was put on the temperatures that could be recovered, the temperatures were examined in the context of the results, as for on-site recovery. When investigating the sharing of surplus heat between a large number of sites there were different combinations of source and sinks that may have given different overall recovery potentials. Sites were ordered in the analysis such that the sites with the largest recovery potentials were analysed first. This meant the largest surplus heat sources had the maximum opportunity to identify a suitable demand. This approach did not optimise heat transportation opportunities, but was sufficient for the indicative analysis undertaken here.

2.7 Combining recovery options

For a particular technology to be suitable for use with a given surplus heat source, the source needs to meet the requirements specified above: the temperature and magnitude may need to exceed specified limits, and a demand must exist for the output of the technology. Figure 2 summarises the requirements on the surplus heat source for the technologies examined. The requirements shown for reuse on-site in Figure 2 are identical for heat transport. The information represented in Figure 2 is based on the methodology detailed above. This was developed to utilise the information available, rather than a strict representation of each technology. For example, on-site recovery could occur with a surplus heat source at less than 100°C, but due to the temperature banding of heat demands only temperatures of 100°C or over were considered for recovery on-site here.

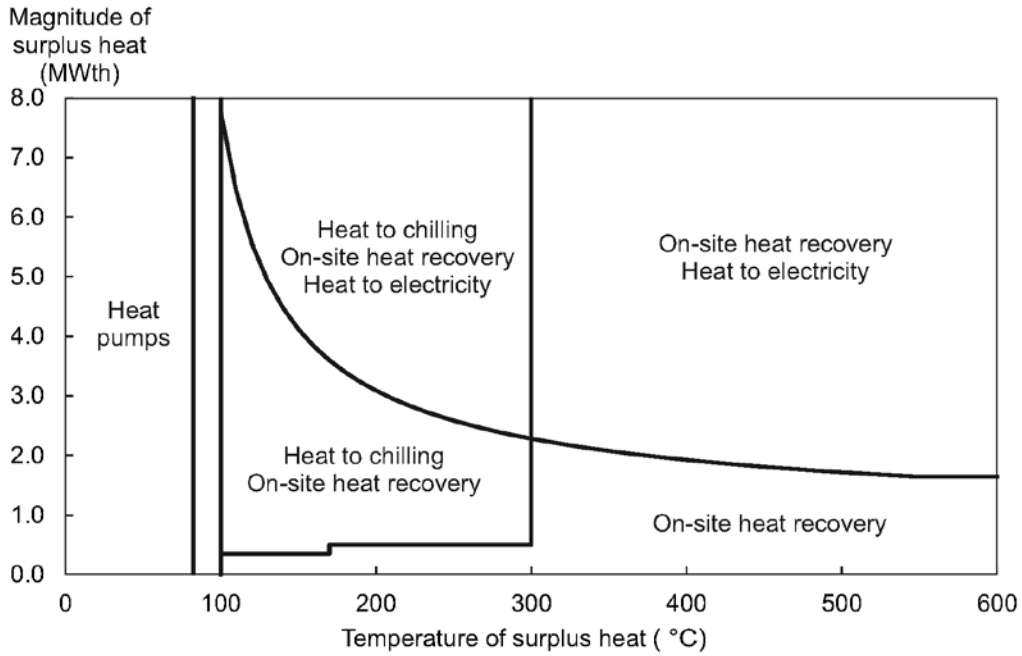

Figure 2 Surplus heat source characteristics required for use by different technologies.

Figure 2 shows that for some surplus heat sources it was only possible to utilise a single technology. However other heat sources could be utilised by a number of different technologies. Additionally it was possible that a single heat source could be used by multiple technologies. For example, if a surplus heat source was used to meet an on-site demand and the demand was less than the identified surplus heat source, it may also be possible to use the remainder of the surplus heat in another technology, such as converting the surplus heat to electricity.

When applied to an identified surplus heat source the technology options examined here vary in the final energy demand saved, the GHG emissions saved, and the exergy saved. For each site in the assessment the combination of technologies that maximised each of these savings was calculated. Heat transportation was not included in this assessment of combined technologies due to the large uncertainties involved in its application. In calculating the energy and emissions savings it was assumed that a heat demand supplied by surplus heat would otherwise have been supplied by natural gas with an 80% efficiency, and that electricity would otherwise by supplied via the UK grid. For absorption chillers, it was assumed that alternative electrical refrigeration equipment would be used with a COP of 4. Emissions factors were taken from DEFRA/DECC guidelines for company reporting [28]. Only direct (operational or 'stack') emissions were accounted for, in the case of electricity this being the emissions occurring when the final electricity demand was generated. For electricity the exergy saved (or required, in the case of heat pumps) was equal to the energy saved. If a heating, or cooling, demand was filled the exergy saved was calculated by multiplying the energy supplied by the Carnot efficiency (equation 2). Where a heat demand was met by the surplus heat source then, in reference to equation 2, T_P was the temperature of the heat demand met and T_0 was the environment temperature (taken as 25°C). The temperature of a given heat demand was assumed to be the mid-point of the temperature band in which the demand existed (or 60°C for the below 100°C temperature band). For a chilling demand, in reference to equation 2, T_P was the environment temperature (25°C) and T_0 the chilling temperature demand (assumed to be 4°C). For a fuller description of the calculation and use of exergy the reader is referred to other publications (for example [22, 29, 30]).

3. RESULTS

3.1 Heat demand and surplus heat sources

Figure 3 shows the annual heat demand by temperature band for the 425 sites involved in the current analysis. This excludes heat demand currently filled by CHP systems. The total heat demand represented was 503PJ/yr.

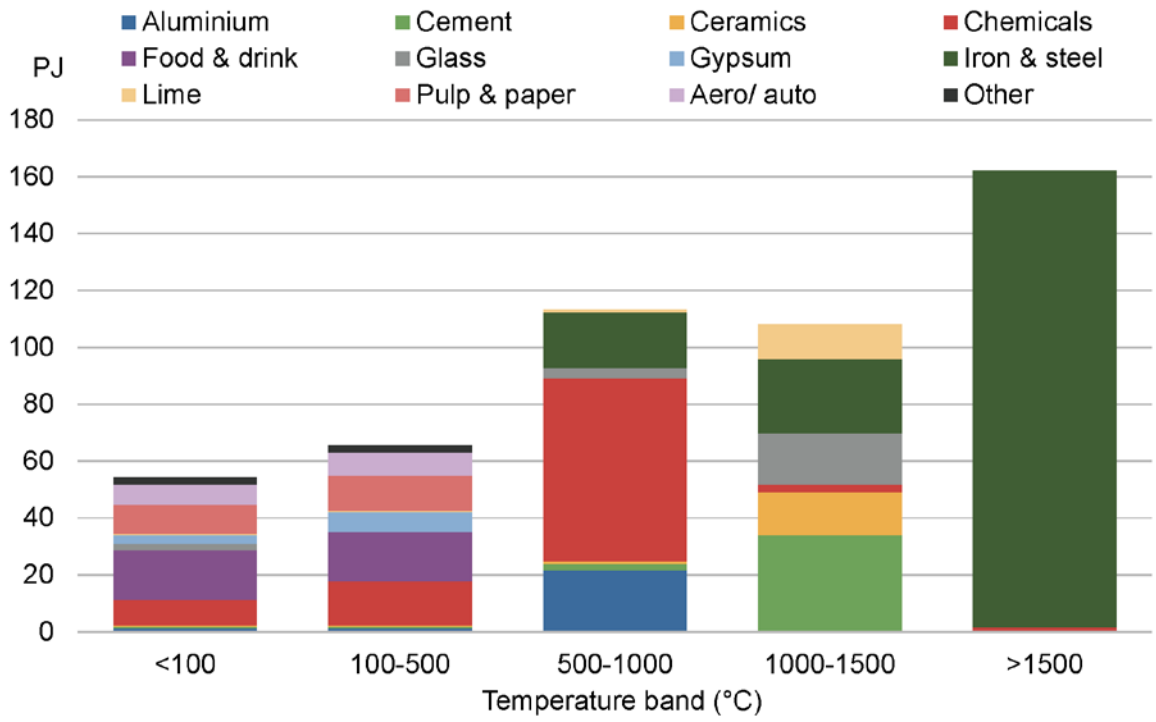

Figure 3 Annual heat demand, by temperature band and subsector, excluding demand supplied by CHP.

Figure 4 shows the surplus heat sources identified. Due to the uncertainty surrounding the recovery potential a range was adopted in defining the magnitude of the surplus heat sources. The recovery potential shown in Figure 4 represents the mean of this range. The total surplus heat available was estimated at 37-73PJ/yr.

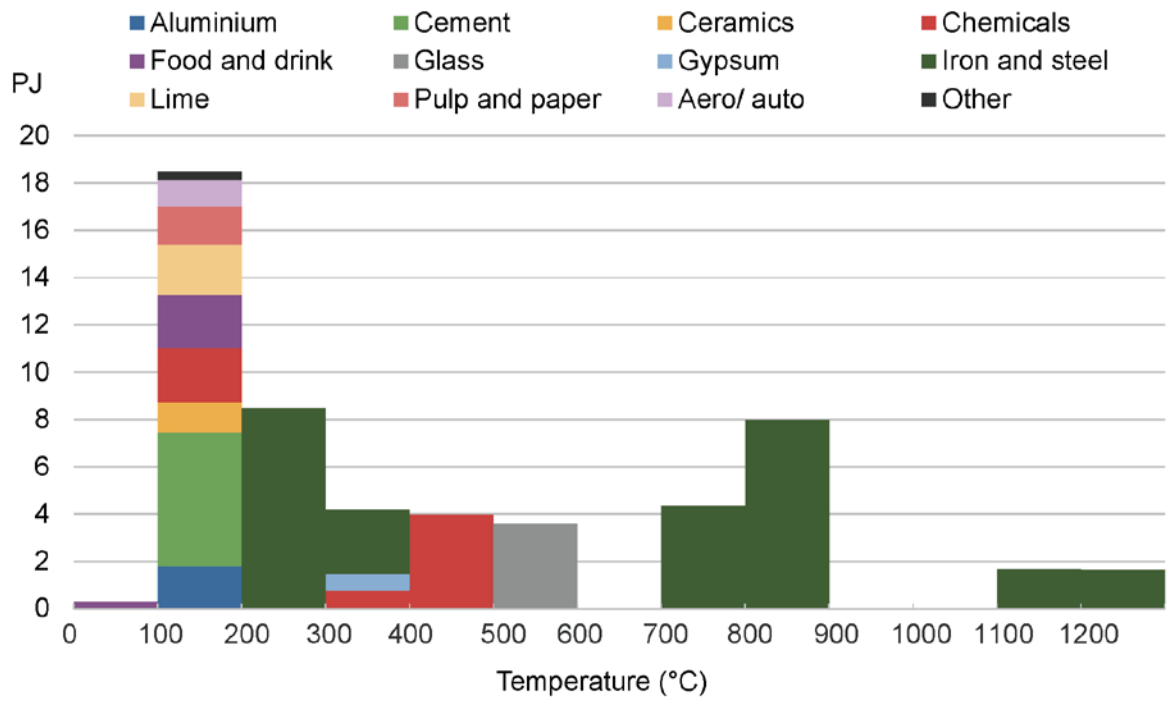

Figure 4 Annual energy available from surplus heat sources, by temperature band and subsector. Mean results shown.

Figure 5 shows the annual heat recovery potential per site by subsector. The Iron and Steel subsector is not shown, although it has a heat recovery potential of some 1500-3000TJ/site/yr.

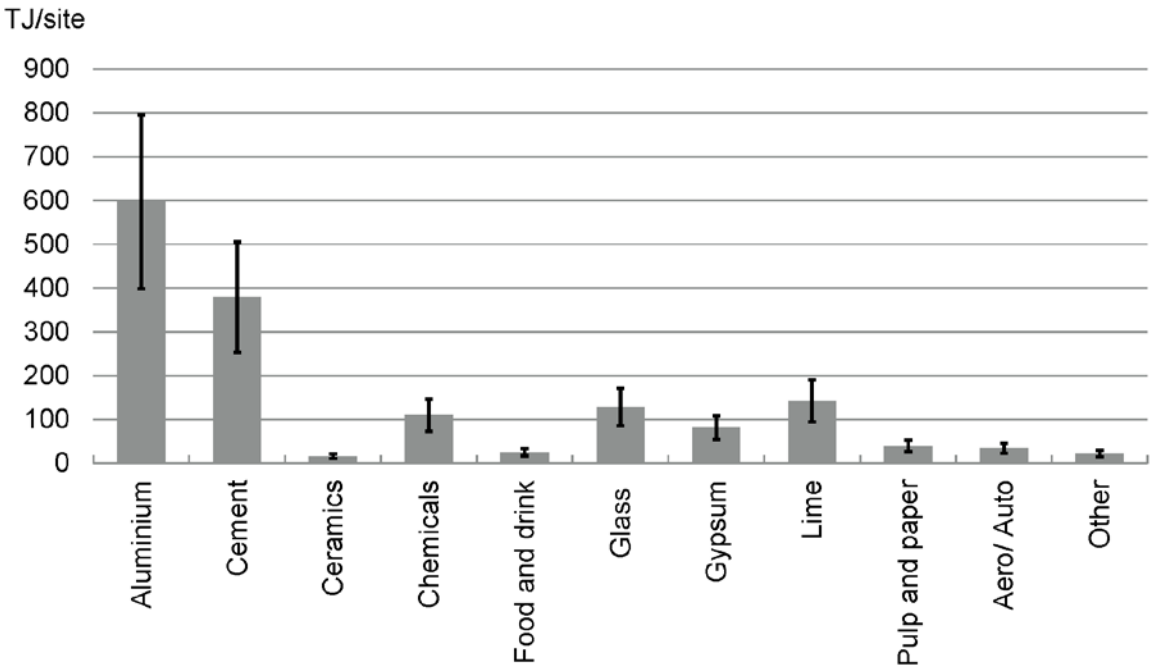

Figure 5 Annual energy available from surplus heat sources per site, by subsector.

3.2 On-site heat recovery

Figure 6 shows the annual on-site heat recovery potential by subsector. Error bars represent the range in the results when using the minimum and maximum estimations of the magnitude of surplus heat sources. The small range for some

subsectors indicates recovery on-site was limited by the existence of a suitable demand rather than the availability of surplus heat. The total amount of surplus heat that could be reused on-site was calculated as 15-23PJ/yr.

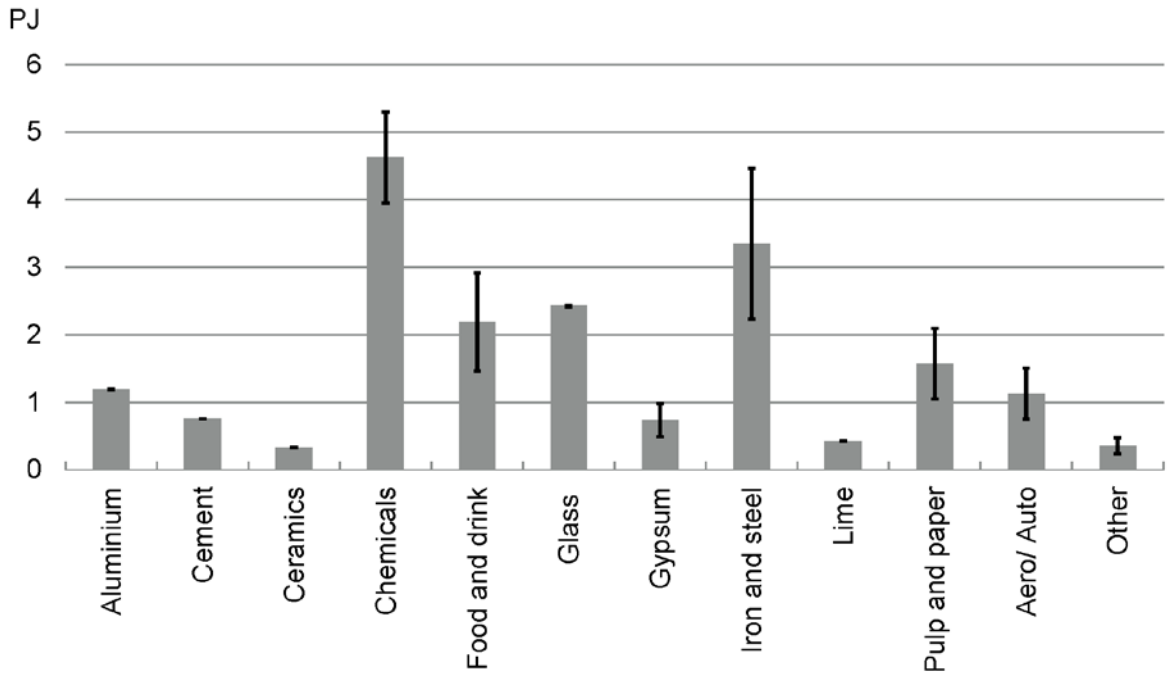

Figure 6 Annual surplus heat recovered for use on-site, by subsector.

For each subsector, Figure 7 shows the proportion of total surplus heat identified that could be used for on-site recovery, and the proportion of sites in each subsector that were able to use on-site recovery. The results are shown for the mean heat recovery potential. The results indicate either that there were many sites for which recovery on-site was possible, but the heat demand was not large enough to utilise the entire recovery potential (also indicated by the lack of error bars in Figure 6), or that a small number of sites that cannot conduct recovery on-site comprise a large proportion of the total potential. Both of these effects were present. 35% of the energy available within the surplus heat sources could be used with on-site recovery, and on-site recovery could occur at 92% of sites (both these values are for the mean heat recovery). A small number of sites dominate in terms of providing most of the potential on-site recovery. Of 393 sites where on-site recovery potential was identified half the sites contribute less than 10% of the total on-site heat recovery potential. The thirty sites with greatest on-site recovery potential comprise half the total recovery potential.

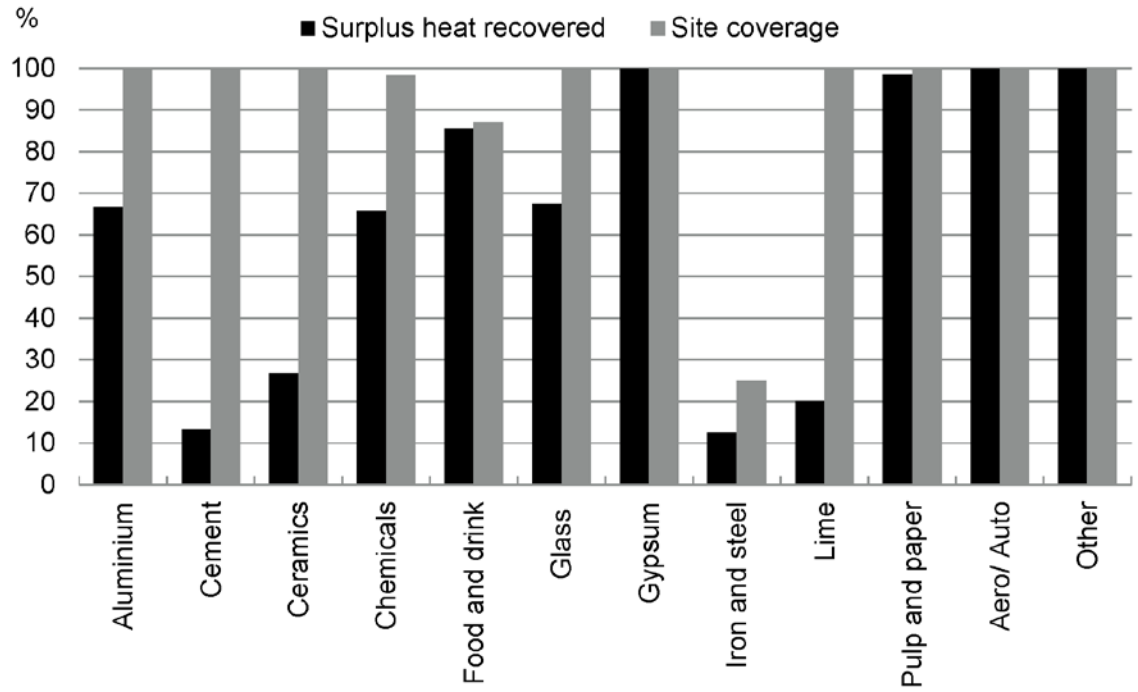

Figure 7 Proportion of total energy available from surplus heat sources utilised by on-site recovery, and proportion of sites at which this is possible, by subsector.

Figure 8 shows the temperature band in which heat was recovered, by subsector. It can be seen that the majority of recovery potential is used to fill a demand in the <100°C temperature band. The temperatures of surplus heat (see Figure 4) are, on the whole, too low to fulfill demand in other temperature bands. This <100°C temperature band has the smallest demand of any of the temperature bands (see Figure 3), limiting recovery on-site. The Iron and Steel sector shows potential for recovery at higher temperature bands, with recovery from the 1000-1500°C temperature band to fulfill a demand in the 500-1000°C band identified in the current analysis.

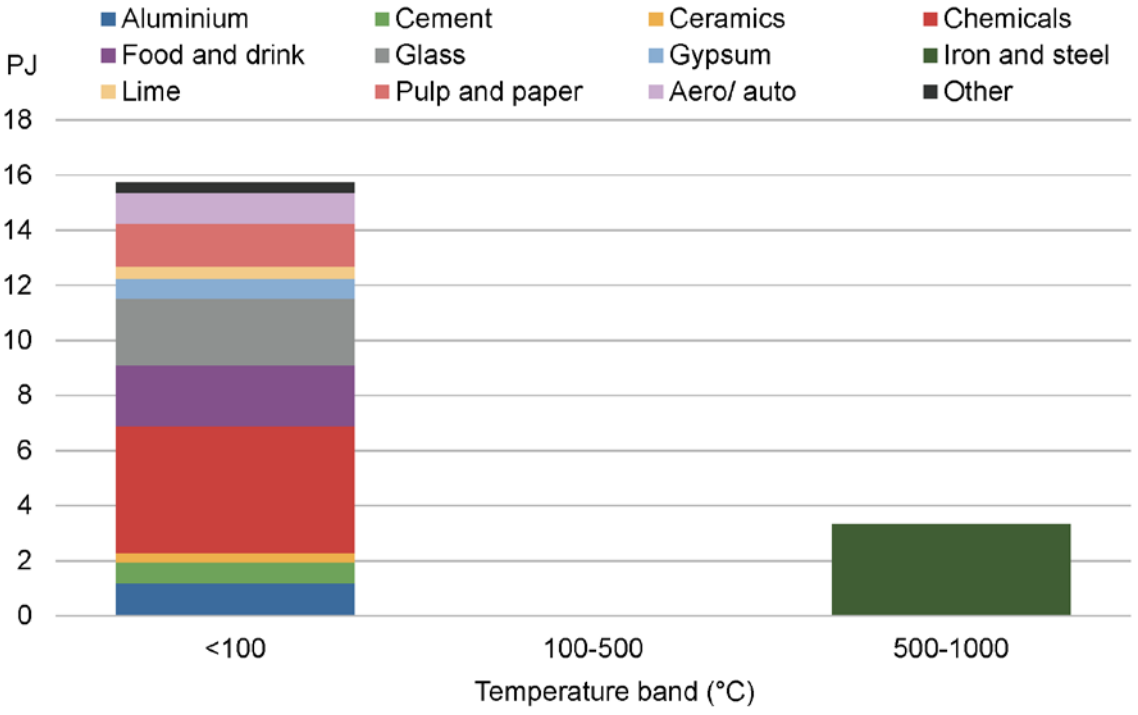

Figure 8 Annual surplus heat recovered for use on-site, by temperature band and subsector.

3.3 Heat pumps

There were two subsectors in the analysis that had a surplus heat source at less than 100°C, and so were possible candidates for the use of heat pumps in utilising surplus heat. These were the Malting and the Distilleries subsectors of Food and Drink. The Distilleries subsector had a surplus heat source at 80°C, so was not considered suitable for current heat pump technology. In the Malting subsector heat recovery potential was at 40°C, and a large demand existed in the 0-100°C temperature band. Malting requires large amounts of air at 62-85°C [31]. Assuming a mean delivery temperature of 75°C gave a COP of 4.3 for a heat pump in this application. The heat that could be delivered at the three Malting sites, using heat pumps, was therefore some 54-109TJ/yr. Individual heat pumps would deliver around 0.5-2.1MW of heat. The heat that could be supplied in this manner represented 6-12% of the total site heat demand. This would result in an electricity demand for the heat pumps of 0.23kW per kW of heat supplied.

3.4 Heat to chilling

Figure 9 shows the possibility for using absorption chillers to recover surplus heat. 2.5-5.9PJ of surplus heat was identified as the annual potential for reuse in absorption chillers. This would supply around 1.7-4.1PJ/yr of chilling capacity. The majority of this capacity would be in the form of single effect chillers. According to the present analysis, the proportion of total surplus heat that could be reused with absorption chilling technology was 82% in Food and Drink and 31% in Chemicals. The proportion of sites at which this technology could be used was 66% in Food and Drink and 67% in Chemicals.

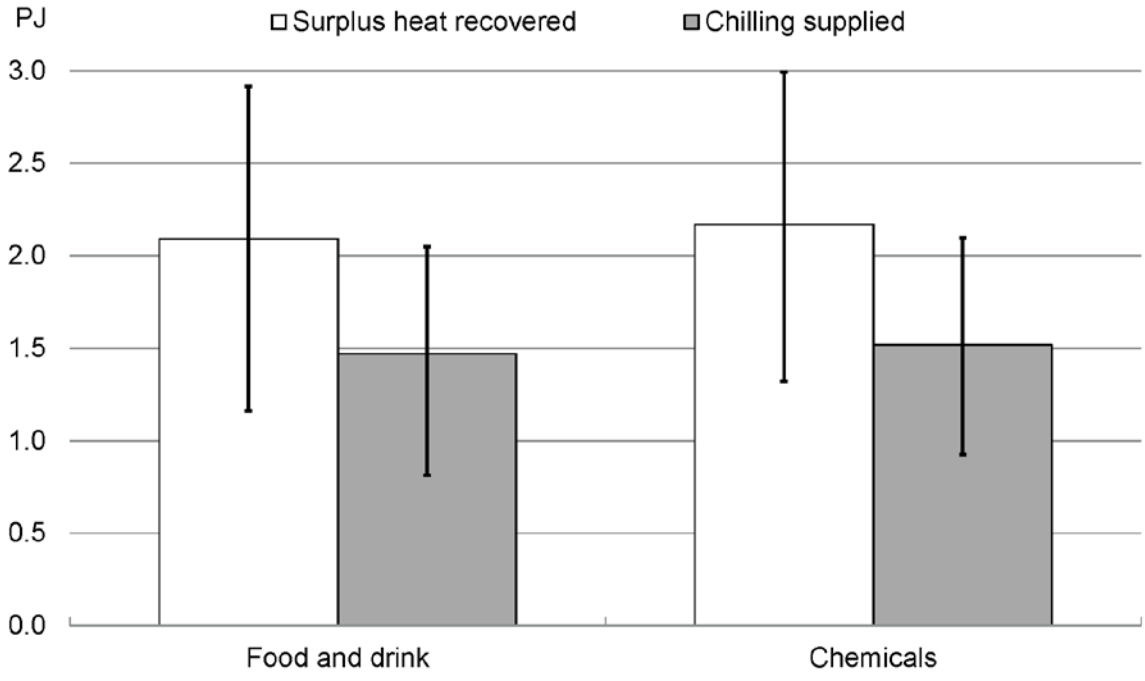

Figure 9 Annual surplus heat recovered and chilling energy supplied through absorption chillers, for the Food and Drink and Chemicals subsectors.

3.5 Heat to electricity

The heat used and electrical energy output, when utilising heat to electricity technologies, are shown in Figure 10. The Iron and Steel sector is not shown in Figure 10 as it dominates the output. It is estimated Iron and Steel would recover some 17.9-

35.8PJ/yr from surplus heat sources, to supply 4.5-9.0PJ/yr of electricity. In total 29-64PJ/yr of surplus heat, supplying 6.7-14.0PJ/yr of electricity, was identified for use in heat to electricity technologies.

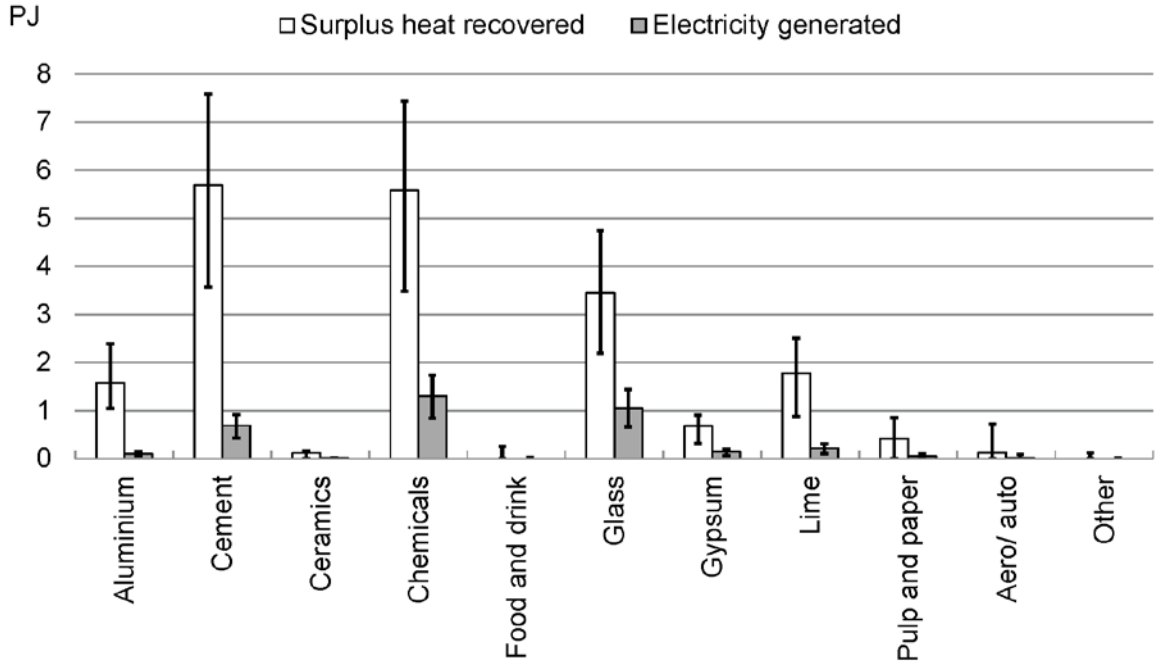

Figure 10 Annual surplus heat recovered and electricity output from heat to electricity technologies, by subsector.

Figure 11 shows the proportion of total surplus heat recovered through heat to electricity technologies and the proportion of sites at which this was possible. The results shown are for the case of the mean heat recovery potential. There was little potential in those subsectors with a low amount of surplus heat per site. This is especially so where the temperature of surplus heat was also low, limiting the efficiency of heat to electricity conversion. In these cases it was not possible to generate more than 0.5MW_e, the minimum required output specified in this analysis (see Figure 2). It was possible to convert 80-87% of surplus heat to electricity, but at only 18-26% of sites. This reaffirms that a small number of sites dominate the overall heat recovery potential. Out of 95 sites with heat to electricity recovery possible, 12 made up over half of the electrical output. There was especially good potential identified in the Iron and Steel and Cement subsectors, which both showed poor opportunities for on-site recovery (see Figure 7).

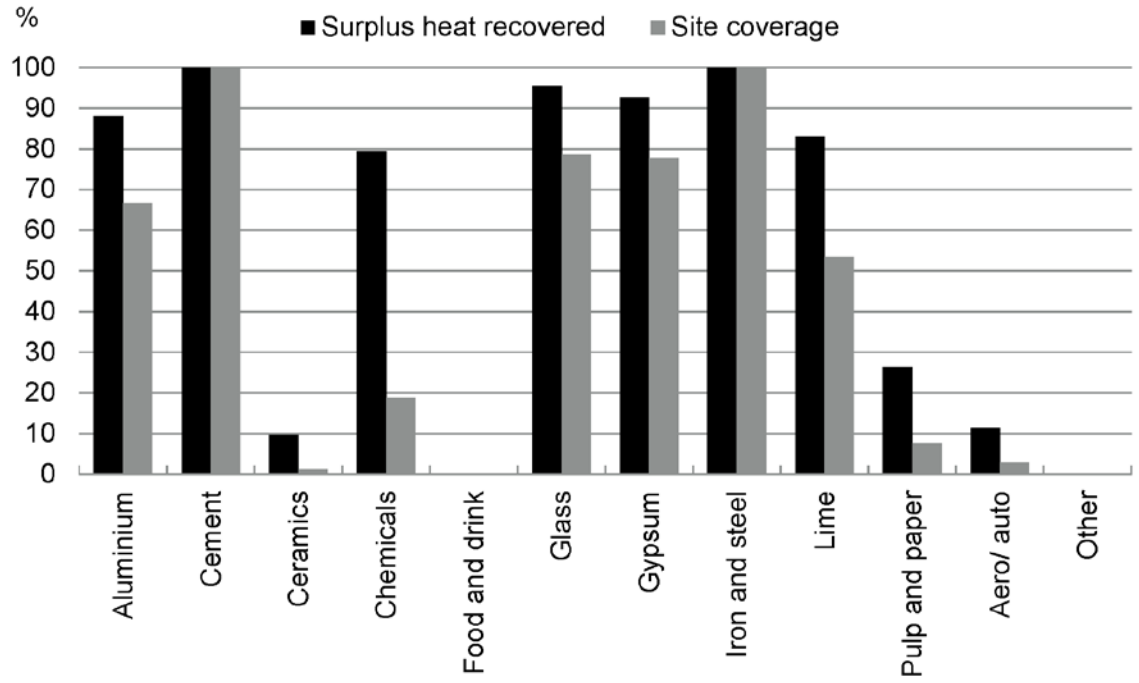

Figure 11 Proportion of total energy available from surplus heat sources utilised by heat to electricity technology, and proportion of sites at which this is possible, by subsector.

3.6 Heat transportation

Figure 12 shows the potential for transporting surplus heat between industrial sites as the distance that it was possible to transfer the heat varied. The error bars represent a combination of the uncertainty in both the magnitude of surplus heat sources and the efficiency of the heat transport process. The points represent the case of mean surplus heat magnitude and a 50% transportation efficiency. Figure 12 shows what would be available to the user of the heat, rather than the surplus heat recovered at the original site.

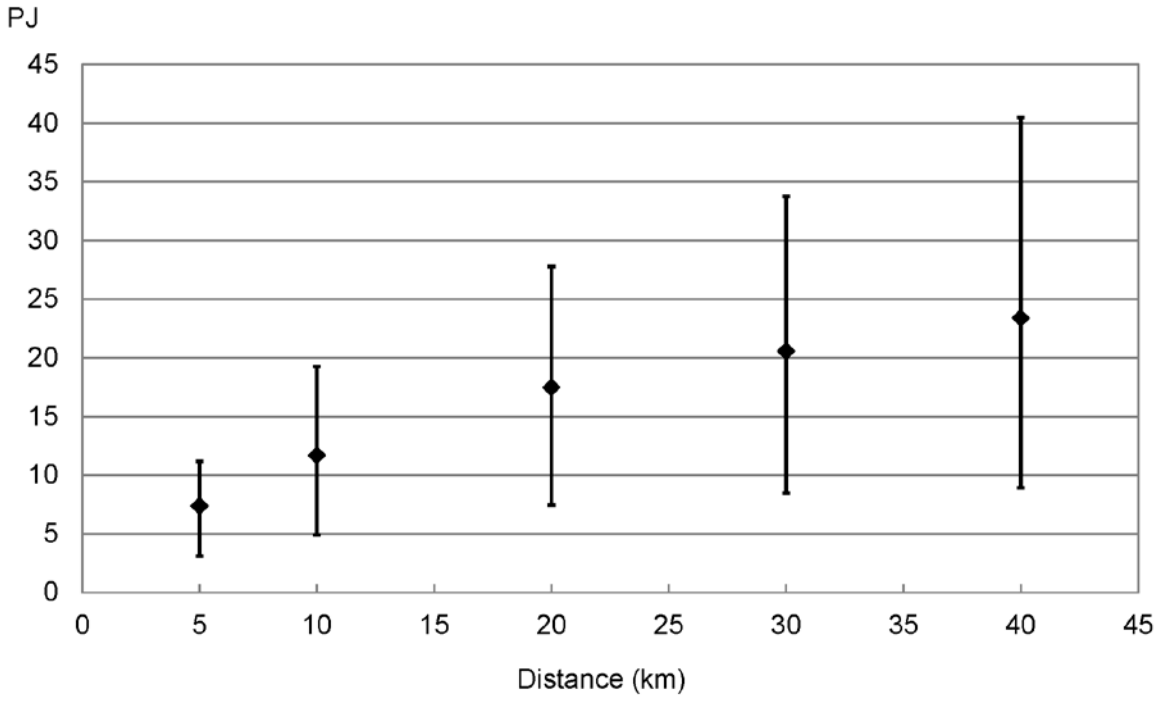

Figure 12 Annual heat demand filled through transportation of surplus heat, as distance and efficiency varies.

Figure 13 shows the subsectors and temperature bands where a heat demand was filled, with a possible transportation distance of 10km, and an efficiency of 50%. In total this represents 23.4PJ/yr of surplus heat, recovered from 280 sites, to supply 11.7PJ/yr of heat demand at 201 sites.

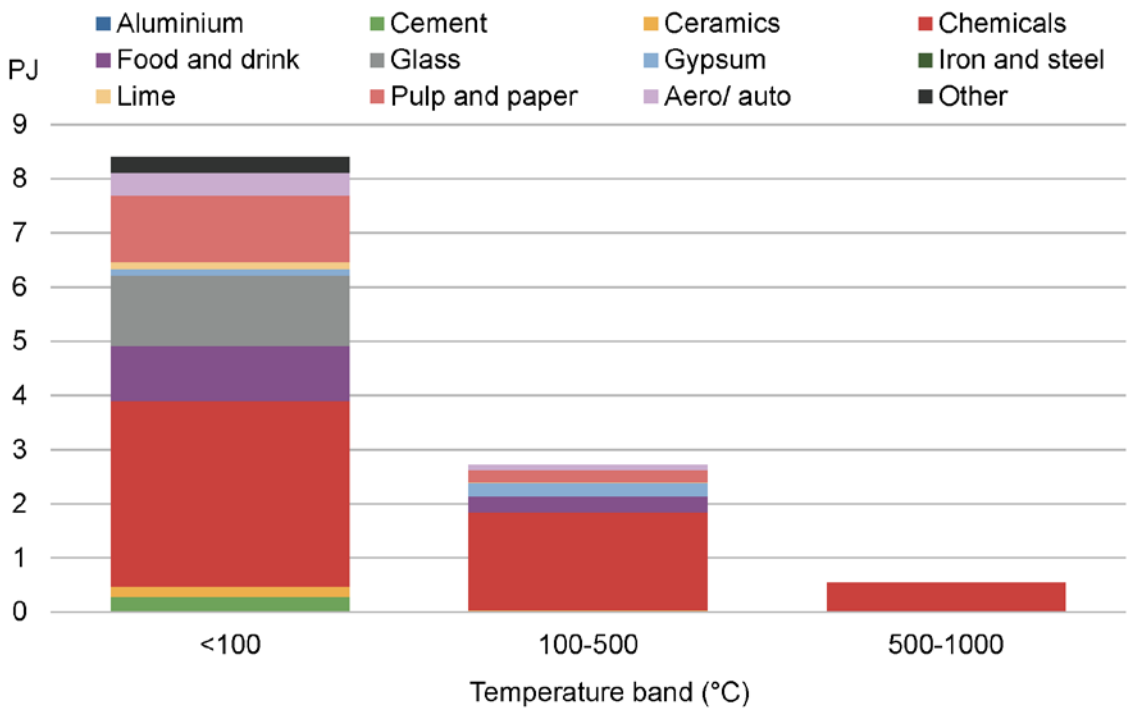

Figure 13 Annual heat demand filled through transportation of surplus heat, by temperature band and subsector. Results with a 10km possible transportation distance and 50% efficiency shown.

Over half the energy recovered in Figure 13 would be from just 15 sites, with 10 sites representing over half the demand for this heat. The potential for a heat network around these large sources and demands may be attractive. Figure 14 shows geographically where sites involved in this heat transportation were located. The area of the data points indicates the magnitude of surplus heat recovered, or heat demand filled. A large potential exists around the integrated iron and steel plant in Teesside (in the North East of England). Likewise a large number of sites around Chester (in the southerly part of England's North West region) show potential for a heat network in addition to relatively smaller clusters near Falkirk (in the centre of Scotland), South Wales and the Thames estuary.

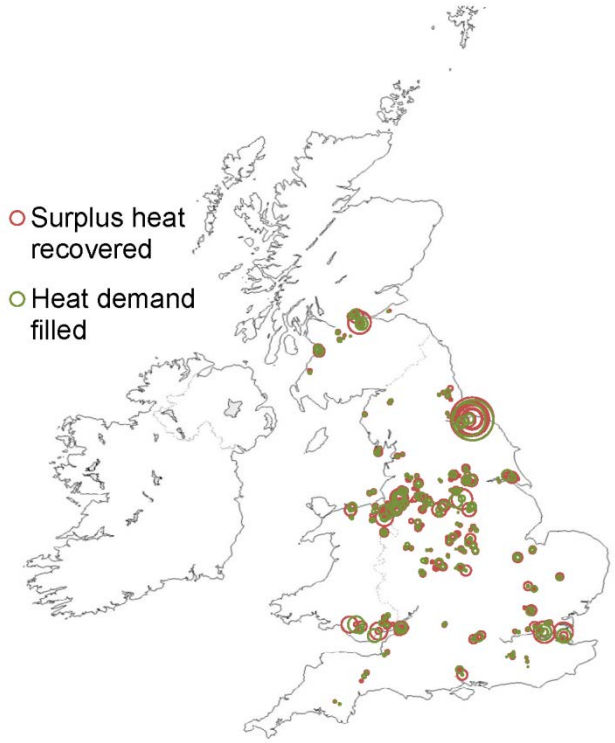

Figure 14 Location of recovered surplus heat sources and end user demands, assuming a 10km possible transportation distance and 50% efficiency. Area of points represent the magnitude of surplus heat recovered or the heat demand filled.

Figure 15 shows in which subsector surplus heat was recovered and where heat demands were filled, with a possible transportation distance of 10km. The surplus heat recovered was greater than the demands filled, due to the inefficiencies in transporting the heat. The error bars represent a combination of the uncertainty in both the magnitude of surplus heat sources and the efficiency of the heat transport process.

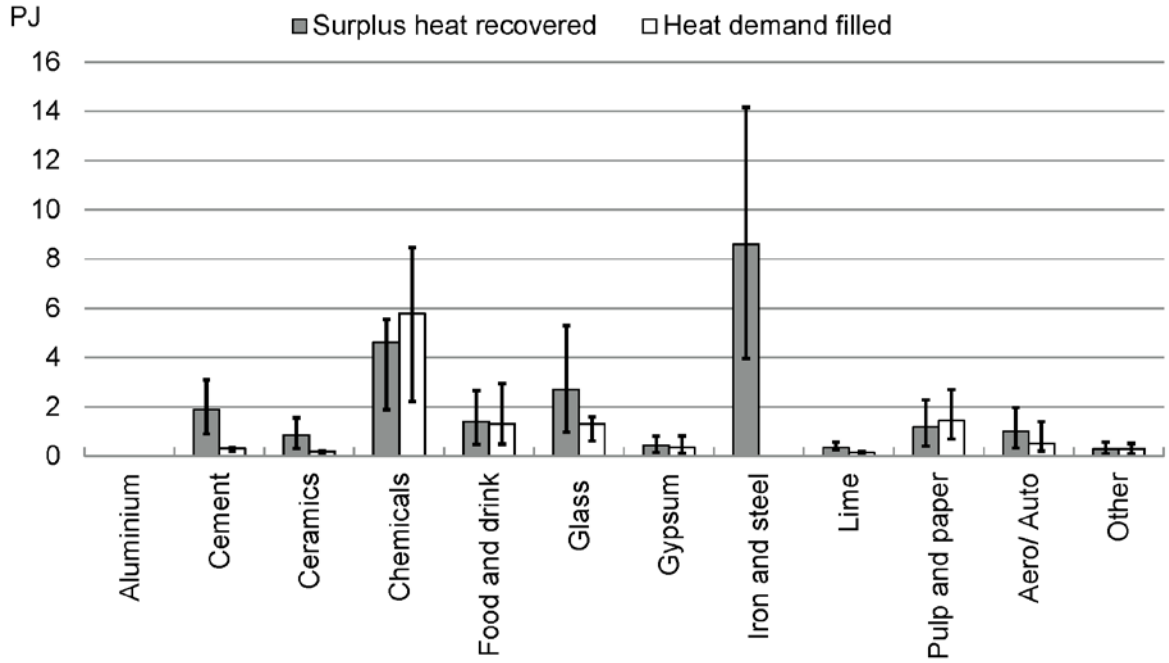

Figure 15 Annual surplus heat recovered and heat demand filled through transportation of surplus heat, assuming a 10km transportation distance, by subsector.

3.7 Combining recovery options

Table 1 shows the final energy saved, exergy saved and GHG emissions saved when a combination of heat recovery technologies were applied to maximise each of the savings. When maximising final energy demand and GHG emissions very similar results were obtained (they are equal to the accuracy presented in Table 1). Maximising exergy savings causes a small increase in the exergy saved (9.5% over the case of maximising energy savings) whilst more significantly influencing the energy savings (a 25% reduction compared to when energy savings were maximised) and emissions savings (an 11% reduction compared to when energy savings were maximised).

	Energy saved (PJ)	GHG emissions saved ($MtCO_{2e}$)	Exergy saved (PJ)
Energy saving maximised	31.3	2.2	11.4
GHG emissions saving maximised	31.3	2.2	11.4
Exergy saving maximised	23.4	2.0	12.4

Table 1: Final energy, GHG emissions and exergy savings when each is maximised by the combination of technologies adopted in utilising the identified surplus heat.

Figure 16 shows the annual heat recovered in each of the subsectors when final energy demand savings were maximised at each site. The Iron and Steel subsector is not shown, it would recover around 3.3PJ/yr for use on-site and 23.5PJ/yr through heat to electricity technology. The results shown are for the case of the mean estimation of surplus heat magnitude. The totals shown in Figure 16 are the surplus heat recovered, not the useful energy outputs. After this combination of technologies had been applied there was 2.5PJ/yr (5%) of the identified surplus heat remaining.

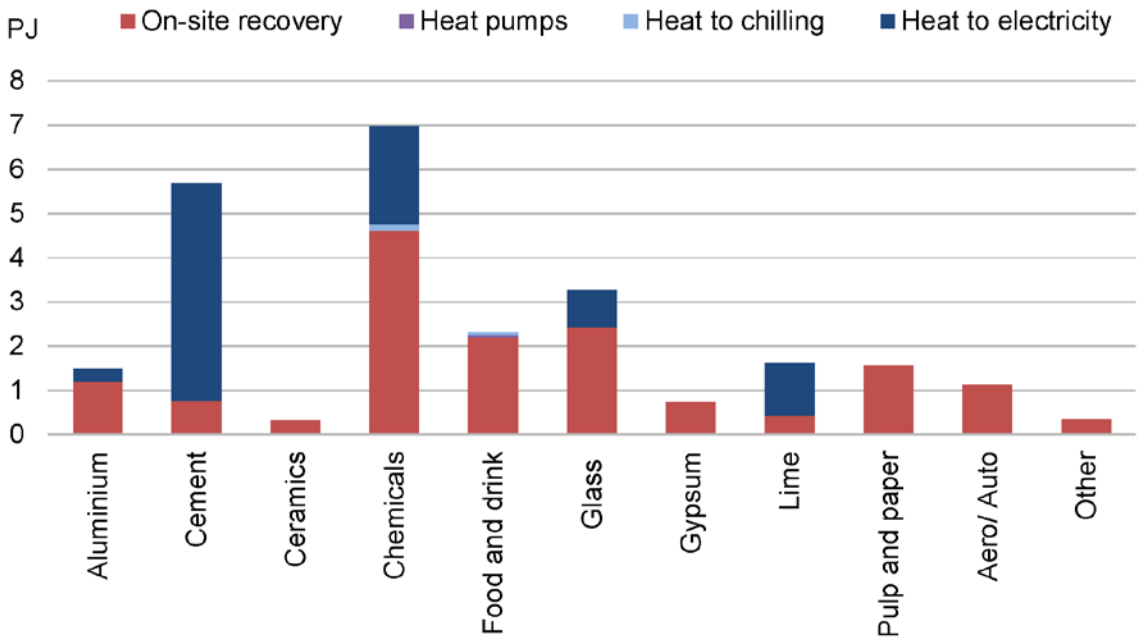

Figure 16 Annual surplus heat recovered through a combination of measures, chosen to maximise final energy demand savings, by subsector.

The heat recovered through on-site heat recovery in this combined case was identical to that when all surplus heat was available. This indicates on-site recovery maximises energy savings, where a suitable demand is available, irrespective of the

surplus heat characteristics. Only heat pumps utilise surplus heat at less than 100°C (see Figure 2) and so their use is unaffected by other technologies. This potential is not shown in Figure 16 as it is insignificantly small compared to the other technologies. The use of heat to provide chilling drops to just 0.06PJ/yr in the Food and Drink subsector and 0.14PJ/yr in Chemicals (from 2.1 and 2.2PJ/yr respectively). Heat to electricity technology now recovers 33PJ/yr. This is compared to 46PJ/yr when all surplus heat was available for use in heat to electricity technology. Most of this loss of potential comes from the Chemicals subsector reusing surplus heat through other technologies.

Figure 17 shows the potential GHG emissions saved through recovering surplus heat. Results are shown both for the case of all heat being available for a particular technology and the combined case, with emissions savings maximised. For comparison purposes, onshore wind electricity generation in the UK totaled 4036.7MW of capacity and generated 7137MWh in 2010 [1]. Assuming the mean emissions factor for the grid this saved approximately 3500ktCO_{2e}.

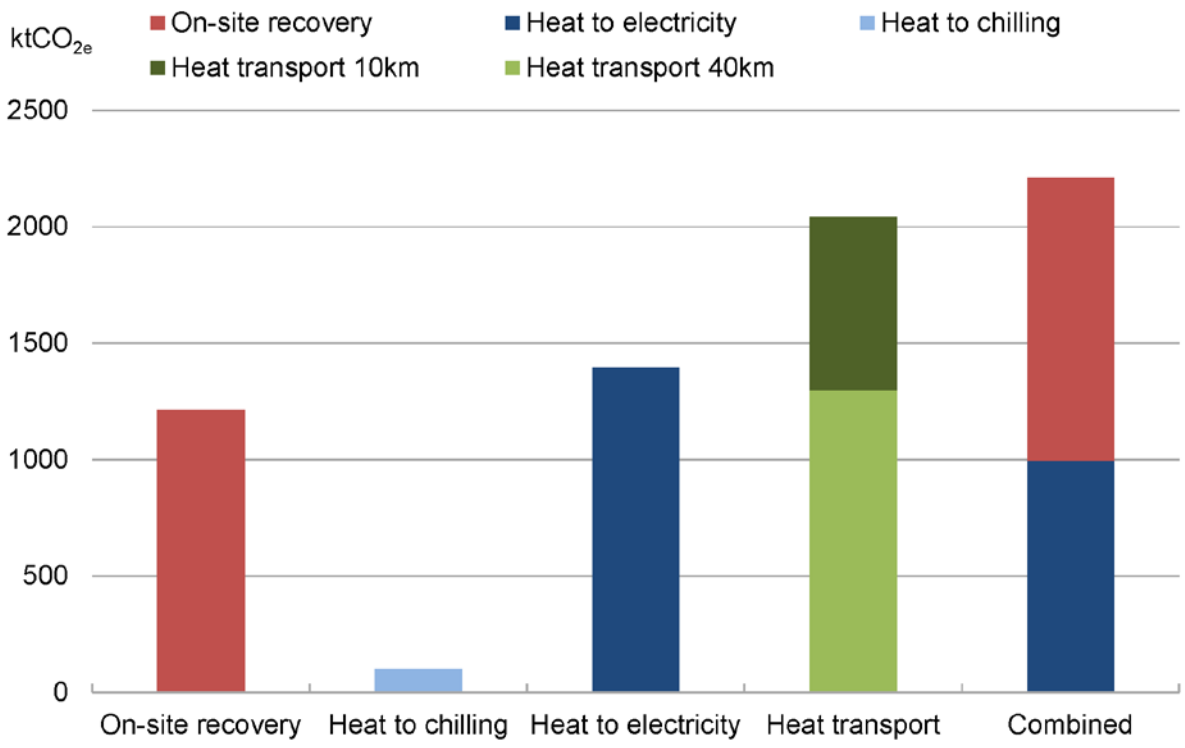

Figure 17 Annual GHG emissions savings by reusing surplus heat through a number of technology options. The combined case selected technologies to maximise emissions savings.

4. DISCUSSION

4.1 Onsite heat recovery

The potential for UK industrial heat recovery on-site was estimated at 15-23PJ/yr. For perspective, this is equal to the space and hot water heating demand for approximately 272,000-418,000 homes[3], or 3-5% of the heat demand for the sites analysed here. The majority of this on-site potential involved recovery at low temperatures (below 100°C). If the temperature of the surplus heat source (assumed to be a gas) drops below its dew point, water condenses and can deposit corrosive substances on the heat exchanger [5]. To avoid this, the minimum temperature in the heat exchanger is limited to 120-175°C [5]. To recover below the dew point temperature more advanced materials and regular maintenance can be

[3] Based on 18,600kWh mean energy use per household and 82% of domestic energy being used in space and water heating [32].

adopted [5], although this is not without expense. These costs could potentially be lowered by further research and development into low temperature heat exchangers. If the temperature of the surplus heat source is lowered below the dew point the latent heat is released, this can contain a significant proportion of total enthalpy in the exhaust gas [5]. The estimates of surplus heat used do not include this latent heat and so further recovery may be possible if it could be captured. Recovery at very high temperatures can be limited without advanced materials [5]. This may add expense, or limit the potential for on-site surplus heat recovery identified within the Iron and steel subsector (see Figure 8).

What could not be accounted for in the current analysis was on-site recovery within the same temperature band that may, in practice, be possible (for example from a surplus heat source of 400°C to a demand at 200°C). More defined temperature demands could allow a more accurate analysis in this regard. In practice, there may also be opportunities to preheat combustion air or product. In this case the heat sink can be at a lower temperature than that specified by the heat demand. However these opportunities are unknown without more detailed studies of specific subsectors and sites. Taking into account these considerations, it is thought that this analysis will likely underestimate the potential for recovery on-site and there may be opportunities to recover heat at a higher temperature that have been overlooked.

4.2 Heat pumps

The potential for heat pump use in industry, as estimated in the current analysis, was limited to a single subsector, Malting. Another study has also indicated that the Malting subsector has considerable potential for heat pumps [33]. In reality, the potential for heat pumps in industry is thought to be significantly higher. A single surplus heat source was identified for each site in the current study. In practice, there will be low temperature surplus heat available from a variety of sources, including compressors and chillers, which can supply surplus heat at 30-60°C [15]. This could well be used as a surplus heat source for heat pumps. Air and ground source heat pumps can also be used within industry to supply low temperature heat where a suitable surplus heat source is not available. Heat pumps currently under development could reach higher temperatures and so increase the potential use of the technology [15-17]. The economic use of heat pumps is highly dependent on the relative price of the conventional heat source (often natural gas, used to fuel boilers) to electricity. Under a decarbonised electricity system heat pumps would become more attractive from an emissions perspective.

4.3 Heat to chilling

The electricity use for chilling in 2005 was 12PJ for Food and Drink and 11PJ for Chemicals [34]. This gives a cooling demand of 48PJ/yr for Food and Drink and 44PJ/yr for Chemicals, assuming a COP of 4 for the refrigeration equipment. Therefore there is sufficient cooling demand to be filled by that potentially generated through absorption chilling of 0.8-2.0PJ/yr and 0.9-2.1PJ/yr for the Food and Drink and Chemicals subsectors, respectively. Whether at the individual site level there is always sufficient cooling demand at the correct temperature to use this technology would require further investigation and may be a limitation on the use of chillers. There may also be opportunities for the use of absorption chillers outside the Chemicals and Food and Drink subsectors. As the air conditioning demand for comfort and for cooling large computer systems increases, the potential to use this technology in other subsectors rises.

4.4 Heat to electricity

Heat to electricity can be an attractive prospect for using surplus heat. Electricity can be used in a wide range of processes and is also relatively easily exported if there is not a sufficient demand on-site (some additional grid connections and expense

may be required in this case). The total demand for grid electricity on the sites included in this analysis was 105PJ/yr. Electricity generated by heat to electricity technology could supply some 6-13% of this demand, or the electricity demand of 422,000-883,000 households[4]. This amount of displaced electricity would save 905-1890ktCO_{2e} annually. The subsectors with the highest potential for heat to electricity technology in the current work, Cement and Iron and Steel, show good prospects for this technology in practice. In the Cement subsector, where surplus heat availability was based on a modern efficient plant [35], the limits to recovering heat for preheating and use earlier in the process are being reached [36]. The remaining surplus heat has found a use in conversion to electricity in some plants [37]. A heat to electricity scheme is planned for the Port Talbot steelworks, based around the Basic Oxygen Furnace (BOF) [20]. It is predicted that this project will produce 10MW of electricity [20]. The predicted output from a heat to electricity scheme on the Port Talbot BOF using the current analysis is around 4.3-8.6MW.

4.5 Heat transportation

The potential for heat transportation is more speculative than other technologies; the possible distance of transportation and efficiency of the transfer being open to considerable uncertainty. The main barriers to the potential for reusing surplus heat between sites are the cost of heat pipelines (or other transportation option) and the security of supply, if one site relies on another for its heat supply (or conversely for income by selling surplus heat) then disruptions in production or closure of one site can considerably affect the other. The existence of a heat network, involving multiple users, and the regulation of such a market (similar to that which exists for electricity, gas and other forms of energy) to protect the stakeholders would facilitate the sharing of surplus heat between sites and may make this option more attractive than other possibilities for reusing surplus heat from industry. Such a heat network could be constructed between multiple industrial users; areas that show good potential in this regard are shown in Figure 14. Linking industrial sites to district heat networks that also supply commercial and domestic users is another option. Maximising the number of users in a heat network for a given area should reduce the cost for each user. In such a network industrial sites could act as both a user of heat, and a supplier of heat. In the UK district heating is currently little used. Approximately half a million homes in the UK are currently supplied by district heating systems [6]. This represents less than 2% of the country's heat demand [38]. Other countries have considerably greater use of this technology with Denmark supplying 70% of heat demands through heat networks, Finland 49%, and Sweden 50% [39]. It is recognised that there are many behavioural factors that mitigate against the adoption of district heating in the UK. Nevertheless, heat networks are capable of adoption on the large scale and are an option that is favoured for reducing energy use and GHG emissions associated with heat demand in the UK by the Department of Energy and Climate Change [39]. Analysis suggests than approximately 50% of heat demand in England is concentrated with sufficient density (3000kWh/km^2) to make heat networks worth investigating [39]. It is likely heat networks would start as small installations, and then expand and become linked to other regional networks over time. Initial priorities in developing heat networks include making use of existing surplus heat resources from industry [39]. Examples of industrial plants integrating with district heating systems include two refineries supplying 30% of the annual heat demand of a district heating system in Gothenburg [40]. Rotterdam also has a heat network for which the main heat source is surplus heat from industry [39]. Recently the possibility of a district heat system supplied by the Port Talbot integrated steelworks has been investigated [41]. Connective Energy, a commercial enterprise set up by the Carbon Trust in partnership with Mitsui Babcock and Triodos Bank used a bottom-up analysis in 2007 to estimate the market potential for surplus heat, by creating a heat network and

[4] Assuming 23.7% of domestic energy demand is electrical [32], giving approximately 4400kwh/yr of electricity demand per household.

facilitating transactions, as 40TWh/yr (144PJ/yr) [6]. Most potential users identified were low temperature industrial processes, showing the suitability of industrial sites for the early stages of expanding heat networks. Industrial sites acting as users in a network have the advantage of often having a year round heat demand. District heat networks generally transport heat at 80-120°C [39], where higher temperatures are required for industrial applications laying steam pipes at the same time as the lower temperature district heating networks can reduce costs. This approach was taken in the Copenhagen network which includes hot water and steam pipelines [39]. Approximately 70% of the potential for heat transportation identified in the current analysis is for recovery in the lowest temperature band, and so this could be recovered with water based transportation systems. Approximately 25% of potential can be recovered in the 100-500°C temperature band, steam-based transportation systems may be viable here. Above this temperature band alternative technologies may be required, these include reversible chemical reactions, phase change thermal storage, absorption and adsorption techniques [27, 42, 43]. According to the current analysis this higher temperature demand represents only a small proportion of the total potential. Further work in this area could combine the analysis here with information on heat demand in other sectors (such as domestically) to assess the potential for combining surplus heat from industry with the expected growth of district heat networks. A more accurate assessment of the potential losses from heat transport could also be completed with more detailed case studies.

4.6 Drivers and barriers

Barriers to the increased use of surplus heat are common to many energy efficiency projects in manufacturing and include lack of capital and competition with production orientated projects [44]; lack of information, staff time and expertise to explore opportunities [44, 45]; and risk aversion to unknown technologies [44-47]. Policies to spread information and financially support research into technologies, demonstration schemes, and investment in such technologies could increase the uptake of heat recovery technology. A review of barriers to energy efficiency projects, specifically focusing on low temperature heat utilisation was recently conducted by Walsh and Thornley [48]. Lack of infrastructure was found to be a key barrier.

4.7 Limitations of the analysis

The analysis presented here is intended to be indicative. It highlights the broad opportunities for recovering heat, rather than precise potentials. Useful additional work would include a detailed assessment of the large recovery opportunities identified at particular sites or subsectors, for example, savings from integrated Iron and Steel sites. An update of the analysis could be conducted for more recent years, with a more recent dataset. Additionally, for certain subsectors, the estimations of heat demand and recovery potential could be improved (see the earlier work [7]). There are also alternative methods to reuse surplus heat not examined here. These include supplying heat demands that were not identified in the current work, such as space heating and biomass drying. Options for the reuse of surplus heat that may become more viable in the future include water desalination and hydrogen production [49].

Reusing surplus heat is essentially the exploitation of what would otherwise be waste, due to the inefficiencies in a process. The adoption of more efficient production technologies may therefore limit the surplus heat available in future time periods. Additionally changes in the output of UK industry, which can be influenced by economic growth and the material demand of the economy, could considerably affect the availability of surplus heat. Such considerations were considered outside the scope of the present study.

5. CONCLUSION

The majority of the surplus heat identified at the UK industrial sites in the analysis can fulfill a demand for heat, chilling or electricity by utilising a variety of recovery technologies. Recovery of the surplus heat for reuse on-site at a low temperature band (less than 100°C) and the conversion of heat to electricity show the greatest technical potential. The use of surplus heat in this manner is possible, but not widespread, within industry. The overall surplus heat recoverable using a combination of these technologies was estimated at 52PJ/yr, saving approximately 2.2Mt$CO2_e$/yr in comparison to supplying the energy demands in a conventional manner. This is an estimate of the technical potential for savings, which will be lower than the maximum theoretical potential, represented by the thermodynamic potential, but likely greater than the economic potential [50]. Reduction of costs through policy supporting the development and adoption of relevant technologies; or higher energy and carbon prices would likely accelerate the use of surplus heat in this manner. A network and market for trading in heat and the wider use of district heating systems could open considerable potential for exporting heat from industrial sites to other users.

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