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HEAT RECOVERY OPPORTUNITIES IN UK MANUFACTURING

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ABSTRACT

A database of the heat demand, heat recovery potential and location of UK industrial sites involved in the EU Emissions Trading System, was used to estimate the potential application of different heat recovery technologies. The options considered for recovering the heat 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 electrical power, 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 the use. The overall heat recoverable using a combination of these technologies was estimated at 52PJ/yr, saving 2.0MtCO_{2e}/yr in comparison to supplying the energy outputs in a conventional 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.

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

NONMENCLATURE

Abbreviations

CCAs	Climate Change Agreements
CHP	Combined Heat and Power
CO_2	Carbon dioxide
COP	Coefficient of performance
CRC	Carbon Reduction Commitment
EU ETS	European Union Emissions Trading System
GHG	Greenhouse Gas
NAP	National Allocation Plan
ORC	Organic Rankine Cycle

Symbols

η	Energy efficiency
T	Temperature [K]

Subscript

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

1. INTRODUCTION

The UK manufacturing 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 which 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 manufacturing sector the requirement to meet legislation designed to limit energy demand and carbon emissions (such as the EU ETS, CRC and CCAs), set alongside the increasing costs of energy [3], represent strong drivers to reducing energy demand.

The requirement for heat represents 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, or waste, heat can, in certain cases, be recovered and utilised to fulfill an energy demand. This replaces conventional energy sources, and so reduces energy costs and associated emissions. Potential uses for the heat include reuse in the same process, or elsewhere on site at a lower temperature level, upgrading the heat, for use at a higher temperature, conversion to chilling capacity, conversion to electrical power and transport to fulfill an off-site heat demand.

Heat recovery is commonly practiced in manufacturing, especially in energy-intensive industries, however it is thought that considerable potential still exists. The Office of Climate Change estimated annual surplus heat recovery potential in UK industry at 18TWh (65PJ) in 2008, this figure was based on conservative estimates and considerable uncertainty [6]. Based on data mainly derived from the Phase II UK National Allocation Plan (NAP) of the EU ETS [7] McKenna and Norman [8] estimated the surplus energy that could technically be recovered from those sites in the EU ETS (approximately 60% of total industry and 90% of energy-intensive industry energy demand) as 36-71PJ/yr, this was a conservative estimate. The information in the NAP represented the manufacturing sector between 2000-2004. This estimate did not identify uses for the surplus heat.

The current work extends the analysis of McKenna and Norman [8], identifying uses for the surplus heat potential. A methodology is developed for identifying heat recovery opportunities using heat exchangers, heat pumps, absorption chillers, heat-to-power technology and transport for off-site uses. The results if all heat recovery potential was available for each technology are presented, in addition to a case where the surplus heat is utilised through a combination of different technologies.

2. METHODOLOGY

2.1 Dataset

For each site in the NAP of the EU ETS (supplemented with additional information on large energy users) information on location, heat demand, and estimated heat recovery potential was available from previous work [8]. For each site, based on emissions or output data and the classification of the site into one of 33 subsectors, 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) and the heat recovery potential was estimated (at a single temperature). A range in the power available as surplus heat was used, representing the uncertainty in this value. For the current work any heat demand currently fulfilled by CHP plants was removed. This demand was already met in an energy efficient manner, and so it was not felt appropriate to replace it with surplus heat. There were 425 sites included in the analysis.

The data used refers to the situation from 2000-2004 with heat demand and recovery potential based on the mean emissions recorded in these years with the highest and lowest figures removed. Since this period energy demand in manufacturing has reduced, due in part to the economic recession experienced in the UK. Energy demand in manufacturing fell by 20% between 2004 and 2010, with the majority of this drop being from 2008-2009 [9]. Some large users of energy have ceased operations, the Teeside integrated iron and steel works was mothballed in February 2010 [10], but has since changed ownership [11], with the blast furnace due to be relit in December 2011 [12], although this has been delayed at the time of writing (January 2012) [13]. There have also been plans to cut jobs and production at the Scunthorpe integrated iron and steel works [14]. Additionally two of three Aluminium smelters have been closed, or closure is planned [15, 16]. The long term future of these plants and how much the capacity of other plants may change in response, is uncertain. The information presented here is unaltered from that for the 2000-2004 period.

2.2 On-site heat recovery

Reusing heat on-site can be achieved most simply by mixing the source of heat (often a flue gas), with the heat demanding medium (such as the product entering a combustion chamber). This approach only requires the installation of ducting and possibly a pump and control system. Where this is not possible due to contamination issues or other constraints a heat exchanger may be used to transfer heat between two fluids, whilst keeping the fluids separate. For heat transfer to take place the temperature of the heat source must be above that of the heat sink.

The temperatures of the source and sink in heat recovery are limited by the materials used in the heat exchanger. Heat exchange can happen at up to 425°C with carbon steel, stainless steel raises this to 650°C and advanced alloys to 900°C, above this temperature ceramic materials can be used [5]. Obviously price increases with more advanced materials. Air bleeding can be used to lower the temperature of the heat source [5]. That is the introduction of air at a lower temperature than the flue gas so that the temperature of the heat source is lowered, whilst the enthalpy available remains constant. This allows less expensive heat exchangers to be used with a high temperature heat source, but also limits the heat sink to having a lower temperature (and so the process will have a lower exergy efficiency [17]). Low temperature limits are also imposed on heat exchange. If the temperature of the flue gas drops below the 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]. This restriction both prevents heat demands below this temperature being met by heat recovery and limits the proportion of heat that can be recovered at higher temperatures, as latent heat released by condensing water contains a significant proportion of enthalpy in the exhaust gas [5]. To recover below this temperature more advanced materials and regular maintenance can be adopted [5], this is not without expense however. In the current analysis limitations to the temperature that can be recovered are not imposed, so that the heat recovery possible without economic constraints is estimated.

Efficiency of heat transfer in a heat exchanger is dependent on a number of factors such as the fluids involved and material of the heat exchanger [18]. The heat recovery potential identified here is what is technically recoverable rather than all surplus heat available [8], the efficiency of heat transfer is already assumed to have been applied in this conservative estimate, no further heat transfer efficiency is imposed. There may also be some additional energy requirement for heat recovery associated with pumps and control systems required as part of the heat recovery system. This will be small in comparison to the heat recovered however [19] and is ignored in this analysis.

For each site in the analysis if there is a heat demand in a temperature band below the temperature of the surplus heat than heat recovery takes place. All, or part, of the surplus heat can be recovered in this manner, dependent on the size of the demand. Sites that are classed separately in this analysis can exist at the same location. One example of this is the integrated Iron and steel sites, where different parts of the steel making process are classed as different sites. There are other situations where sites in different subsectors are based at the same location. The use of heat from one of these sites at the other is classified as heat reuse-on-site. Reusing heat at the same site (rather than same location) is prioritised. Additionally when considering the recovery options if multiple heat demands can be filled by the recovery potential the highest temperature demand is prioritised, maximising the exergy efficiency of the heat transfer process.

2.3 Heat pumps

Whilst heat exchangers are used to channel the natural flow of heat from a higher to lower temperature, heat pumps use an external energy source (usually an electric motor) to reverse this flow, 'upgrading' heat from a lower to a higher temperature [20]. Current technology allows temperatures of 100-190°C to be reached (dependent on the technology used), with a temperature lift between source and sink of up to 90°C possible [20, 21]. Costs are greater for those heat pumps at higher temperatures, with current practice being for heat pumps to provide heat to 80°C, with 140°C expected to reach market by 2015 [22]. For the current analysis this limits the use of heat pumps to supply a heat demand in the lowest temperature band (less than 100°C) using a heat source within the same band.

Heat pump performance is defined by the coefficient of performance (COP), which is the ratio of heat output to work input. The maximum theoretical COP (Carnot COP) is defined by the temperatures of the heat source and heat supply [22]. The COP reached in practice is approximately 55% of the Carnot COP [22]. An expression for the COP of a heat exchanger can therefore by derived:

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

T_D is the temperature of delivered heat and T_P the temperature of the heat source. The additional terms (±5) are 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 drive the heat transfer between the refrigerant and the environment. If a surplus heat source exists at less than 80°C the possibility of using a heat pumps is investigated and the COP calculated to determine the heat output and electricity input required for each site.

2.4 Heat for chilling

Absorption chillers are a form of heat pump technology where a heat source is used to provide chilling [23]. When there is both surplus heat and a cooling load absorption chillers can provide an effective solution. There are two widely available types of technology available, single effect units use heat at approximately 100°C to supply chilling with a COP of 0.7 [24]. Double effect units use heat at 165-180°C to provide chilling with a COP of 1.0 [24]. The minimum output from commercially available units is around 350kW of chilling capacity [24]. 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 the surplus heat available with the above technologies is estimated.

2.5 Heat-to-power

Converting surplus heat to electrical energy represents another option for the reuse of waste heat. Many conventional power stations convert heat to power using a Rankine cycle [25]. A similar approach can be used with waste heat if it is of a sufficient temperature and power. At lower temperatures a number of alternative cycles can be utilised, these include the organic Rankine cycle (ORC) [26], the Kalina cycle [27], Inverted Brayton cycle and Stirling engine [28]. The most well established of these in converting waste heat to power is the ORC, which substitutes the water used as the working fluid in a traditional Rankine cycle with an alternative fluid, allowing operation at lower temperature ranges and output powers. Technologies that generate electricity directly from heat, rather than through a cycle that first converts the heat to mechanical energy (as in the examples above), are in the development stage. These technologies include thermoelectric, thermionic and piezoelectric devices, they are however yet to be tested in industrial waste heat applications and would currently be prohibitively expensive [5].

The traditional Rankine cycle and ORC are the technologies used to estimate heat-to-power potential here. There are examples of both being used successfully in industrial waste heat-to-power applications [29, 30]. Generally at higher temperatures the traditional cycle is used, whilst at lower temperatures an organic fluid is required. However other factors such as the composition and power of the heat source influence at what temperature one technology takes preference over the other. As an approximate measure water is generally used as the working fluid at temperatures above 400°C [5, 19, 29]. Although there are instances of Organic working fluid being used with a source temperature of approximately 500°C [5, 31].

The theoretical efficiency of converting heat-to-power 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 [32]:

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

T_0 is normally defined by the environment and so relatively constant (taken as 25°C here). Therefore the higher T_P (in this case the waste heat temperature) the higher the possible efficiency of its conversion to electrical power. Figure 1 shows the Carnot efficiency for converting heat to power at different source temperatures alongside the net efficiencies at different temperatures reported by four manufacturers of ORC systems [31, 33-35] and a typical efficiency of a steam Rankine cycle at 550°C [25]. A logarithmic curve has been fit to this data to estimate the efficiency of a heat-to-power cycle at a given temperature.

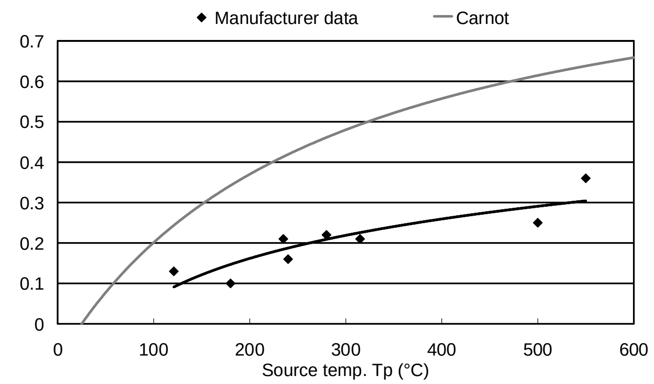

Figure 1 Theoretical and practical First Law efficiencies of heat-to-power cycles.

In the current study whether water or an organic fluid will be used in the Rankine cycle is not specified. The expected efficiency of a technology is based on the trend line shown in Figure 1 and varies with the temperature of the surplus heat, rather than the technology used. The minimum power output for a viable heat-to-power project is set at 0.5MW. This is based on information obtained from manufacturers of ORC systems [31, 34, 35]. This required output is combined with information on efficiency to define the required power of waste heat at a given temperature. The minimum temperature of waste heat required for an ORC system can be as low as 66°C if appropriate working fluid is selected [5]. However in practical applications 90°C was found to be the limit [29] and information obtained from manufacturers indicates 120°C [31, 34, 35]. For the current study 100°C was adopted as the minimum required temperature for a heat-to-power application. There is also a maximum temperature for which heat can be used in the Rankine cycle. This is approximately 550°C, without resorting to expensive materials [25]. This is therefore taken as the upper limit for heat-to-power with waste heat sources at higher temperatures being considered but with the assumption that air bleeding is used and so a limit is imposed on the efficiency of heat-to-power conversion.

2.6 Heat transportation

It is possible to transport heat between locations so the recovery potential from one site can fulfill a demand at another. The most well established technology for this purpose, which is used in district heating networks is via a pipeline utilising the sensible and/ or latent heat of water. There are a wide range of other technologies, that are in the development stage and not known to currently be used in practice. These technologies are based on reversible chemical reactions, phase change thermal storage, or absorption and adsorption techniques [36-38]. These alternative technologies may deliver advantages in terms of the economically feasible distance that heat can be transported and the possible temperature of heat transfer, in comparison to those using water. For example a chemical catalytic chemical reaction has the potential to absorb heat at about 950°C and release heat around 500°C [37].

The distance heat can feasibly be transported is limited by the costs of the transportation network and the losses of enthalpy and exergy encountered. This distance would be expected to vary considerably for different projects and a range of values are given in the literature. It is reported that using water or steam pipelines transportation is limited to 10km at 300°C [37]. At low temperatures as losses to the environment are less there are examples of a Swedish district heating network transporting heat at 120°C for 40km and a pipeline in Iceland carrying heat at 90°C for almost 70km [6].

The efficiency of the heat transportation is also open to considerable variation for individual projects. For this reason figures are not often quoted in literature. One study simulated efficiencies of heat transportation over 30km, efficiency with a hot water or steam based system was 32%, this increased to 53% using a chemical reaction based system using methanol, and 75% using a double stage methanol process [37].

For the current analysis due to these uncertainties heat transportation distances between five and forty kilometers were examined. The efficiency of this heat transportation was assumed to be 50±25%. No restriction was put on the temperatures that could be recovered, these can be examined in the context of the results, as for recovery on-site

Similarly to recovery on-site surplus heat was used to fulfill a heat demand in a lower temperature band. When investigating the sharing of surplus heat between a large number of sites there are different combinations of source and sinks that may give different overall recovery potentials. Attempting to optimise the analysis to calculate the maximum heat that can be transported to other sites presents a difficult problem and is not felt to be required here as the results are only considered indicative. The sites in the analysis were ordered so that the sites with the largest recovery potentials were analysed first (therefore having a greater opportunity to identify a demand for the heat).

2.7 Heat recovery hierarchy

The heat recovery options presented above vary in the likely capital cost, which is likely to be the greatest barrier to the application of the heat recovery options. The analysis therefore considers two cases for each option. Firstly when all the identified recovery potential is available for use with the given technology. Secondly when the heat available is limited by other technologies having already used some of the available heat.

The general hierarchy for the use of a heat source is the same as the order in which the technologies are presented here, namely heat recovery on-site, heat pumps, conversion to chilling energy, conversion to electrical power and transport to another site [29]. There will be exceptions to this hierarchy in practice but it forms a sensible approach for the indicative analysis here.

3. RESULTS

3.1 Heat demand and recovery potential

Figure 2 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 heat demand is also split by subsector. The total heat demand represented here is 503PJ.

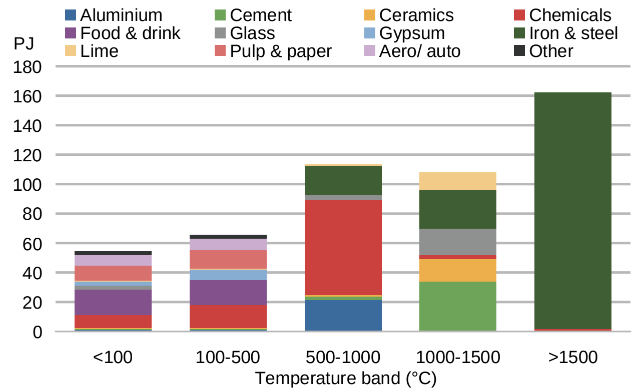

Figure 2 Annual heat demand, excluding demand supplied by CHP.

Figure 3 shows the annual heat recovery potential identified, similarly to Figure 2 it is split by temperature demand and subsector. Due to the uncertainty surrounding the recovery potential a range was adopted in defining the power available. The recovery potential shown in Figure 3 represents the mean of this range. The total surplus heat available is 37-73PJ. This is slightly different to what was found in the original work on which the present contribution draws [8] due to a different treatment of electrical energy use for heating.

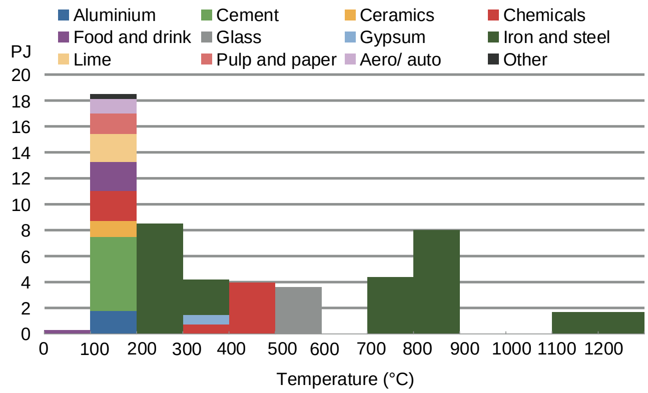

Figure 3 Annual heat recovery potential identified.

Figure 4 shows the annual heat recovery potential per site by subsector. The Iron and steel subsector is not shown, it was a heat recovery potential per site of 1500-3000TJ/site/yr. This indicates the large potentials of the Iron and steel subsector for heat recovery, especially given that the different operations of the integrated sites are classed as different sites in this analysis but are at the same location.

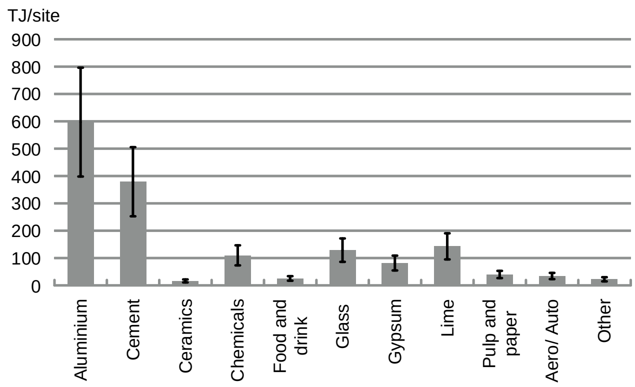

Figure 4 Annual heat recovery per site.

3.2 On-site heat recovery

Figure 5 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 heat recovery potential. The small range for some subsectors indicates recovery on-site is limited by the existence of a suitable demand rather than the availability of surplus heat The total amount of surplus heat that can be reused on-site is 15-23PJ/yr.

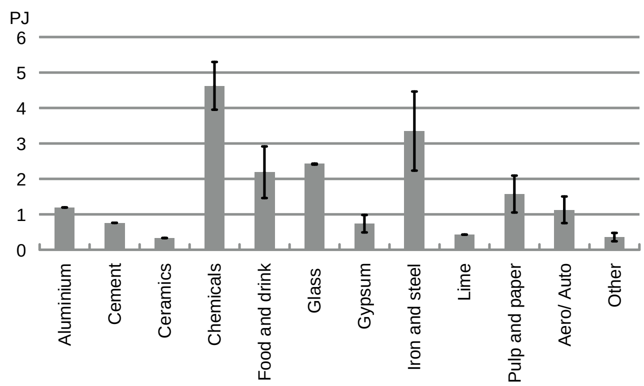

Figure 5 Annual on-site heat recovery.

For each sub-sector Figure 6 shows the proportion of total heat recovery potential that could be used for on-site recovery and the proportion of sites in each subsector that are able to use on-site recovery. The results for the mean heat recovery potential are shown. It can be seen that the proportion of sites at which on-site recovery occurs is greater than the proportion of heat recovery potential recovered on-site. This indicates that there are many sites for which recovery on-site is possible but the heat demand is not large enough to utilise the entire recovery potential. Reusing only part of the recovery potential would likely not be as economic as being able to reuse the full potential. For the industrial sector as a whole 35% of the heat recovery potential can be used with on-site recovery, with recovery occurring at 92% of sites (both these values are for the mean heat recovery). The low amount of recovery within certain subsectors with a high resource of surplus heat (mainly Iron and steel, but also Cement) limits the overall recovery seen.

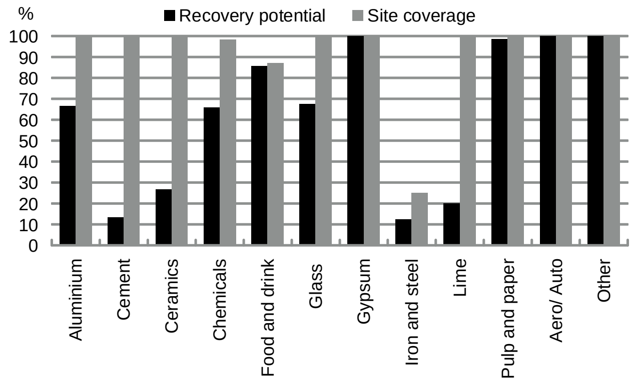

Figure 6 Proportion of total recovery potential realised with on-site recovery and proportion of sites at which on-site recovery is possible.

The majority of recovery potential is to fill a demand in the less than 100°C temperature band. The temperatures of heat recovery (see Figure 3) are on the whole too low to fulfill demand in other temperature demands. This <100°C temperature band has the smallest demand of any of the temperature bands (see Figure 2), limiting recovery on-site. Additionally heat recovery in this temperature range is costly, due to the potential for corrosion of the heat exchangers. 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. Again however this may require advanced materials in the heat exchangers to reuse heat as this high temperature. The most viable temperature for heat recovery is fulfilling a demand in the 100-500°C temperature band. The only example of this in the current analysis is the recovery of heat from a Glass manufacturing site to be reused at a Cement site at the same location. That there is little potential for heat recovery to this temperature band suggests opportunities to do so have already been realised as this is usually the most economic form of heat recovery.

Figure 7 shows the power of heat recovery per site against the number of sites. It can be seen that at low powers, where recovery is likely the least economic there are a large number of sites. There are twelve sites with potential to recover >7MW of heat and not shown in Figure 7. Of 393 sites where on-site recovery potential is 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.

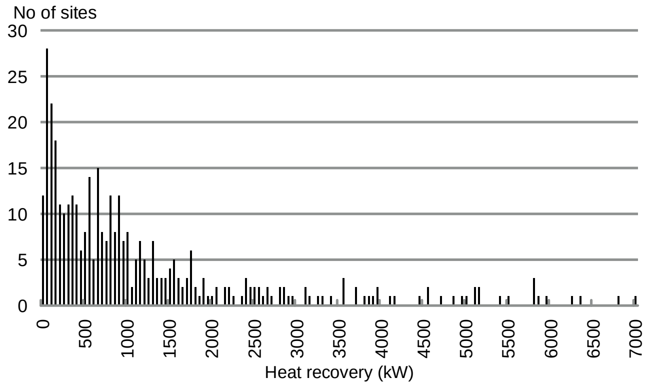

Figure 7 Number of sites recovering heat on-site against power recovered.

3.3 Heat pumps

There are two subsectors in the analysis that have a heat recovery potential at less than 100°C. These are the Malting and Distilleries subsectors of Food and drink. The Distilleries subsector has a recovery potential at 80°C so is not considered suitable for current heat pump technology. In the Malting subsector heat recovery potential is at 40°C, and a large demand exists in the 0-100°C temperature band. Malting requires large amounts of air at 62-85°C [39]. Assuming a mean delivery temperature of 75°C gives 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, is therefore 54-109TJ. The individual heat pumps would deliver 0.5-2.1MW_{th} of heat. The heat that could be supplied in this manner represents 6-12% of the total site heat demand.

3.4 Heat for chilling

Figure 8 shows the possibility for using absorption chillers to recover waste heat. In Food and drink where the heat is generally available at a lower temperature single effect chillers are the dominant technology, where as in the chemicals subsector where higher temperature waste heat is available double effect chillers are in the majority. This leads to a higher efficiency of converting waste heat to chilling capacity in the chemicals subsector (overall COP of 0.9, compare to 0.7 in food and drink). In total 5.6-12.2PJ of surplus heat is identified as the annual potential for reuse in absorption chillers, this would supply 4.9-10.4PJ of chilling capacity annually.

According to the analysis the proportion of total surplus heat that can be reused with absorption chilling technology is 82% in food and drink and 98% in Chemicals. The proportion of sites at which this technology can be used is 66% in food and drink and 80% in Chemicals.

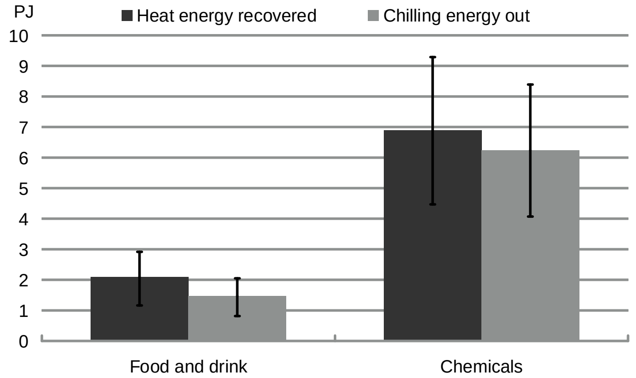

Figure 8 Annual heat energy recovered and chilling energy supplied with absorption chillers.

3.5 Heat-to-power

The heat used and electrical energy output utilising heat-to-power technologies are shown in Figure 9. The Iron and steel sector is not shown in Figure 9 as it dominates the output. It is estimated Iron and steel would recover 17.9-35.8PJ/yr of heat energy to supply 4.5-9.0PJ/yr of electricity. In total 29-64PJ/yr of heat, supplying 6.7-14.0PJ/yr of electricity was identified for use in heat-to-power technologies.

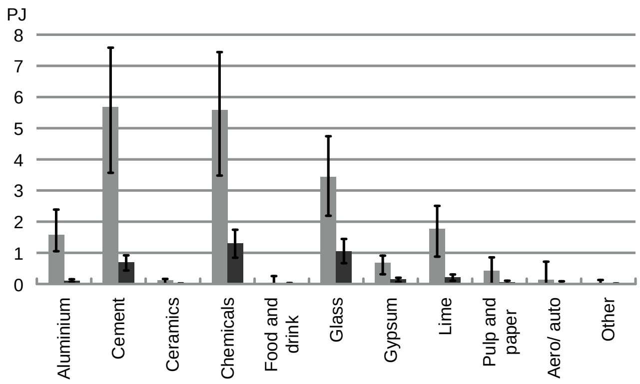

Figure 9 Annual heat recovered and electrical energy output from heat-to-power technologies.

Figure 10 shows the proportion of total surplus heat recovered through heat-to-power technologies and the proportion of sites at which this is possible. The results shown are for the case of the mean heat recovery potential. There is little potential in those subsectors with a low amount of surplus heat per site, this is especially so where the temperature of surplus heat is also low, limiting the efficiency of heat-to-power conversion. In these cases it is not possible to generate more than 0.5MW of electricity, the minimum required output in this analysis. 80-87% of total surplus heat is available to be converted to power but at only 18-26% of sites. This reaffirms the domination of a small number of sites in the overall heat recovery potential.

Out of 95 sites with heat-to-power recovery possible, 12 make up over half of the electrical power output.

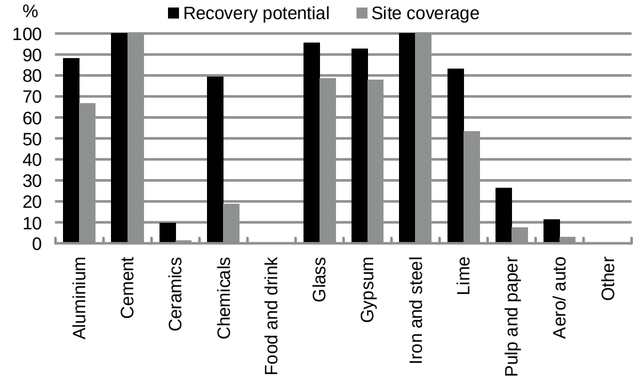

Figure 10 Proportion of total recovery potential realised with heat-to-power recovery and proportion of sites at which this is possible.

3.6 Heat transportation

Figure 11 shows the potential for transporting surplus heat between industrial sites as the distance that it is possible to transfer the heat varies. The error bars are formed from a combination of the range of available surplus heat and the efficiency of the heat transport process (25-75%). The points represent the case of mean surplus heat availability and a 50% transportation efficiency. Figure 11 shows what would be available to the user of the heat, rather than the heat recovered at the original site.

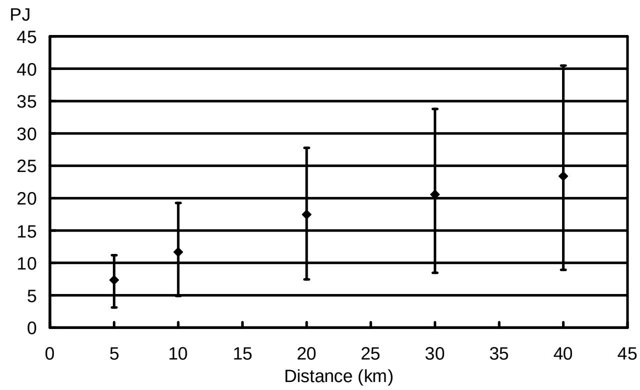

Figure 11 Annual recovery potential by transporting heat as distance varies.

Approximately 70% of the potential identified in Figure 11 is for recovery in the lowest temperature band and so could be recovered with currently available water based transportation systems.

With a transportation distance of 10km and an efficiency of 50% 11.7PJ of heat recovered from 280 sites can be used to supply demand at 201 sites. This represents 43% of all surplus heat. Over half the energy recovered is from just 15 sites, with 10 sites representing over half the recovered demand. The potential for a heat network around these large users and suppliers may be economically attractive.

Figure 12 shows by subsector the heat recovered and where a demand is filled. The total amount recovered is greater than that used due to the inefficiencies in transporting the heat.

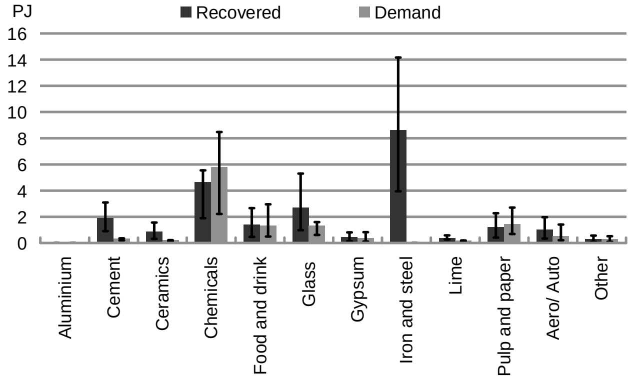

Figure 12 Annual heat recovered and used by subsector with a 10km transportation distance.

3.7 Combined results

Figure 13 shows the annual heat recovered for each of the end uses examined here, where the heat available is dependent on what is left after the more 'attractive' technologies, according the hierarchy above, have been applied. The Iron and steel subsector is not shown, it would recover 3.3PJ/yr for use on-site and 23.5PJ/yr through heat-to-power technology. The results shown are for the case of the mean estimation of surplus heat. The totals shown in Figure 13 are the heat recovered, not the useful output. Two results are shown for heat transportation, firstly for a 10km possible transportation distance and 50% efficiency. What could additionally be recovered with a 40km transportation distance and 75% efficiency is also shown.

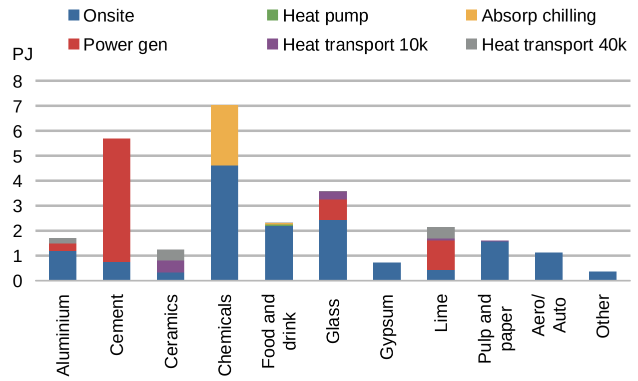

Figure 13 Annual heat recovered through a combination of measures, according to the proposed hierarchy.

All surplus heat is available for on-site heat recovery as before so these results are unchanged at 19PJ/yr. As heat pumps use temperatures less than 100°C the use of this technology is unaffected by on-site heat recovery. Figure 13 illustrates how small this potential is in comparison to other technologies. Surplus heat to absorption chilling drops to just 0.06PJ/yr in the Food and Drink subsector and 2.4PJ/yr in Chemicals (from 2.1 and 6.9PJ/yr respectively). Heat-to-power technology now recovers 31PJ/yr. This is compared to 46PJ/yr when all surplus heat is available for use in heat-to-power technology. Most of this loss of potential comes from the Chemicals subsector reusing surplus heat in other ways. After these options for reusing surplus heat have been applied there is little potential left for transport to other sites. With a 10km transportation distance, 50% efficiency 0.9PJ/yr can be recovered for transportation between sites, if the transportation distance increases to 40km, with a 75% efficiency this increases by 1.1PJ/yr. After the combination of heat recovery technologies have been applied only 0.3PJ/yr of total surplus heat remains.

4. DISCUSSION

The potential for heat recovery on-site is estimated as 15-23PJ/yr. For perspective this is equal to the space and hot water heating demand for approximately 272,000-418,000 homes[1] or 3-5% of the heat demand for the sites analysed here. Assuming the heat supplied would otherwise be produced by a natural gas boiler with 80% efficiency this would save 960-1470ktCO_{2e} annually (using a relevant emissions factor [41]). The majority of this on-site potential involves recovery at low temperatures (below 100°C), which causes additional costs in comparison to recovering at higher temperatures (100-500°C). These costs could potentially be lowered by further research and development into low temperature heat exchangers. What cannot be accounted for in the current analysis is on-site recovery within the same temperature band that may, in practice, be possible (for example from a source of 400°C to a sink of 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, product or other medium where the heat sink can be at a different 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 (limiting the cost of the recovery) that have been overlooked. The conservative nature of the estimation of surplus heat would also likely increase overall potential for on-site recovery.

The potential for heat pump use in industry in the current analysis is limited to a single subsector, Malting. It is confirmed by another study that the Malting subsector has considerable potential for heat pumps [42]. Assuming the heat supplied by heat pumps would otherwise have been supplied with a natural gas boiler, and that the electricity used by the heat pumps is supplied by the national grid the overall annual carbon savings using heat pumps at the malting sites is estimated to be 1.8-3.5 ktCO_{2e}. With a lower carbon electricity supply these savings would be higher. In reality the potential for heat pumps in industry is thought to be considerably higher. A single source of recovery potential is identified for each site. In practice there will be low temperature surplus heat from a variety of sources,

[1] Based on 18,600kWh mean energy use per household and 82% of domestic energy being used in space and water heating [40].

including compressors and chillers which can supply surplus heat at 30-60°C [22]. This could be well used as a source for heat pumps if a sufficient demand exists. 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. 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 will also become more attractive from an emissions perspective.

Assuming absorption chillers would displace those powered by grid electricity with a COP of 4 would mean the 4.9-10.4PJ/yr of chilling energy supplied through the use of surplus heat could save 165-351ktCO_{2e} annually. The electricity use for chilling in 2005 was 12PJ for Food and drink and 11PJ for Chemicals [43]. This gives a cooling demand of 48PJ/yr for Food and drink and 44PJ/yr for Chemicals. Therefore there is sufficient cooling demand to be filled by that potentially generated through absorption chilling of 0.8-2.0PJ/yr and 6.2-8.4PJ/yr for Food and Drink and Chemicals respectively. Whether at the individual site level there is always sufficient cooling demand to use this technology would require further investigation and may be a limitation on the use of the technology. In the Chemicals subsector three sites were identified that had 30MW or greater of chilling capacity using absorption chillers (whilst all other sites has less than 15MW of identified capacity). It is uncertain whether a chilling capacity of this magnitude could be utilised, and so if all the heat could be recovered in this manner. These three sites represent approximately 2.5-5.0PJ/yr of the total chilling capacity identified. There may also be opportunities for the use of absorption chillers outside the Chemicals and Food and drink sectors. As air conditioning for comfort and for cooling large computer systems increases the demand for cooling, other subsectors may also find a use for this technology. With the recovery of heat for use on-site taking preference the opportunity to use absorption chillers is considerably reduced, especially within the Food and drink subsector.

Heat-to-power can be an attractive prospect for using surplus heat. Electricity can be used in a wide range of processes and also relatively easily exported if there is not a sufficient demand on-site (some additional connections and expense may be required in this case). The total demand for grid electricity of the sites included in this analysis is 105PJ/yr. Electricity generated by heat-to-power technology could supply 6-13% of this demand, or the electricity demand of 422,000-883,000 households[2]. This amount of displaced electricity would save 905-1890ktCO_{2e} annually. The subsectors with the highest potential for heat-to-power 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 [44] the limits of recovering heat for preheating and use earlier in the process are being reached [45]. The remaining surplus heat has found a use in conversion to power in some plants [46]. A heat-to-power scheme is also planned for the Port Talbot steelworks, based around the basic oxygen furnace [30]. It is predicted that this project will produce 10MW of electricity [30]. The predicted output from a heat-to-power scheme on the Port Talbot BOF using the current analysis is 4.3-8.6MW. Giving preference to reusing heat on-site and absorption chilling reduces the power generated by surplus heat to 4.2-9.4PJ/yr. That the Cement and Iron and steel subsectors do not have a large potential for recovery on-site means the heat-to-power potential is not reduced excessively.

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. Additionally sharing surplus heat between sites can be difficult, mainly due to security of supply issues. A heat network and heat market (similar to that which exists for electricity, gas and other forms of energy) would facilitate the sharing of heat. Another method to reuse heat, through transportation to another user, would be the involvement of industrial sites in district heating systems. If such a scheme is in existence close to an industrial site it can be a sink for surplus heat or a supplier of low temperature heat. Using surplus heat in an existing district heating system would considerably reduce the capital costs involved in comparison to setting up a transportation system between two industrial sites and help overcome barriers relating to security of supply. In this way surplus heat from industry could supply heat to other industrial sites, as well as commercial and public buildings, and domestic housing. Examples of manufacturing plants integrating with district heating systems include two refineries supplying 30% of the annual heat demand of a district heating system in Gothenburg [47]. Within Denmark 5% of industrial heat demand is supplied through district heating [47]. In the UK the district heating is currently little used. Approximately half a million homes in the UK are currently supplied by district heating systems [6]. The potential for district heating is estimated to be 14% of domestic heating demand (167PJ/yr), with 80PJ/yr going to industry [48]. Connective Energy, a commercial enterprise set up by the Carbon Trust in partnership with Mitsui Babcock and Triodos Bank used a bottom-up study in 2007 to estimate the market potential for surplus heat, by creating a heat network and facilitating transactions, as 40TWh/yr (144PJ/yr) [6]. Most potential users identified were low temperature industrial processes. A considerable potential for integrating industry with district heating is therefore thought to exist in the UK. Recently the possibility of a district heat system supplied by the Port Talbot integrated steelworks has been investigated [49]. When preference is given to reusing surplus heat to fulfill other needs on-site the potential for transporting heat between industrial sites reduces significantly. If district heating networks were in existence the transportation of heat may move up the hierarchy of uses for surplus heat.

[2] Assuming 23.7% of domestic energy demand is electrical [40], giving approximately 4400kwh/yr of electricity demand per household.

The potential savings from the combined recovery options (discounting the heat transported, as this is less likely to be realised with current infrastructure) is estimated at 52PJ/yr. Taking into account the final use of the surplus heat this would save approximately 2.0MtCO_{2e}/yr. This does not account for embodied energy and emissions associated with the recovery options and alternatives. Barriers to the increased use of waste heat are common to many energy efficiency projects in manufacturing and include lack of capital and competition with production orientated projects [50]; lack of information, staff time and expertise to explore opportunities [50, 51]; and risk aversion to unknown technologies [50-53]. 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.

The analysis presented here is intended to be indicative of the situation and used to highlight broad opportunities for recovering heat rather than precise potentials for particular technologies. Useful additional work would be a detailed assessment of the large recovery opportunities identified at particular sites or subsectors, such as integrated Iron and steel sites. There are also alternative methods to reuse waste heat not examined here. These include supplying heat demands that are not identified here 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 [54].

5. CONCLUSION

The majority of the surplus heat identified at the sites in the analysis can fulfill a demand for heat, chilling or power by utilising a variety of recovery technologies. Recovery of the heat for reuse on site at a low temperature band (less than 100°C) and the conversion of heat energy to electrical power show the greatest potential. The use of surplus heat in this manner is possible, but not widespread within industry. 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. The existence of a network and market for heat would open up the potential for transporting surplus heat to an off-site user.

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REFERENCES

[1] DECC. Digest of United Kingdom Energy Statistics (DUKES). London: TSO, 2009.
[2] HM Government. Climate Change Act 2008 (c. 27). 2008.
[3] DECC. Table 3.3.1 Fuel price indices for the industrial sector from Quarterly Energy Prices publication. London: Department of Energy and Climate Change; 2010.
[4] DECC. ECUK: Table 4.7 Industrial energy consumption by end use (different processes) 2008. London: Department of Energy and Climate Change; 2010.
[5] US Department of Energy. Waste Heat Recovery: Technology and Opportunities in U.S. Industry. 2008.
[6] BERR. Heat call for evidence. London: Department for Business, Enterprise and Regulatory Reform; 2008.
[7] DECC. EU Emissions Trading Scheme Approved Phase II National Allocation Plan 2008-2012. London: Department for Environment, Food and Rural Affairs; 2008.
[8] McKenna RC, Norman JB. Spatial modelling of industrial heat loads and recovery potentials in the UK. Energy Policy. 2010;38:5878-91.
[9] DECC. ECUK Table 4.6: Industrial Energy Consumption by fuel type. London: Department of Energy and Climate Change; 2011.
[10] Iron and Steel Statistics Bureau. UK [online]. 2011. Available from: http://www.issb.co.uk/uk.html [Accessed 5th May 2011].
[11] SSI UK. SSI UK [online]. 2011. Available from: http://www.ssi-steel.co.uk/ [Accessed 2nd November 2011].
[12] BBC News. Milestone in Redcar blast furnace return [online]. 2011. Available from: http://www.bbc.co.uk/news/uk-england-tees-15420512 [Accessed 2nd November 2011].
[13] Westcott M. Delay to restart of steel making on Teeside [online]. The Northern Echo. 2011. Available from: http://www.thenorthernecho.co.uk/business/9431344.Delay_to_restart_of_steel_making_on_Teesside/ [Accessed 3rd January 2012].
[14] BBC News. Tata Steel to cut 1,500 jobs in Scunthorpe and Teesside [online]. 2011. Available from: http://www.bbc.co.uk/news/business-13469088 [Accessed 24th May 2011].
[15] BBC News. Final shift at Anglesey Aluminium [online]. 2009. Available from: http://news.bbc.co.uk/1/hi/wales/north_west/8281699.stm [Accessed 2nd November 2011].
[16] Tighe C. Energy costs blamed as Rio axes smelter [online]. London: Financial Times. 2011. Available from: http://www.ft.com/cms/s/0/e37a9546-1078-11e1-8298-00144feabdc0.html#axzz1e3H3ZGpP [Accessed 25th November 2011].
[17] Bejan A, Tsatsaronis G, Moran M. Thermal design and optimization. Chichester: Wiley; 1996.
[18] Goldstick RJ, Thumnann A. The Waste Heat Recovery Handbook. Atlanta: The Fairmont Press; 1983.
[19] Pehnt M, Bodeker J, Arens M, Jochem E, Idrissova F. Industrial waste heat - tapping into a neglected efficiency potential. Proceedings of ECEEE 2011 Summer Study Energy Efficiency First: The Foundation of a Low Carbon Society, 6–11 June 2011 Belambra Presqu'île de Giens, France. 2011.
[20] Soroka B. Industrial Heat Pumps. In: Leonardo ENERGY, editor. Power Quality & Utilisation Guide Section 7: Energy Efficiency. 2007.
[21] IEA Heat Pump Centre. Heat pumps in industry [online]. 2011. Available from: http://www.heatpumpcentre.org/en/aboutheatpumps/heatpumpsinindustry/Sidor/default.aspx [Accessed 13th July 2011].
[22] Hita A, Seck G, Djemaa A, Guerassimoff G. Assessment of the potential of heat recovery in food and drink industry by the use of TIMES model. Proceedings of ECEEE 2011 Summer Study Energy Efficiency First: The Foundation of a Low Carbon Society, 6–11 June 2011 Belambra Presqu'île de Giens, France. 2011.
[23] Horbaniuc BD. Refigeration and Air-Conditioning. In: Cleveland CJ, editor. Encyclopedia of Energy, Volumes 1 - 6: Elsevier; 2004.
[24] US DOE Industrial Technologies Program. Energy Tips - Steam (Sheet #14). Washington D.C.: US DOE, (DOE/GO-102006-2259), 2006.
[25] Boyle G, Everett B, Ramage J. Energy Systems and Sustainability. Oxford: Oxford University Press; 2003.
[26] Tchanche BF, Lambrinos G, Frangoudakis A, Papadakis G. Low-grade heat conversion into power using organic Rankine cycles – A review of various applications. Renewable and Sustainable Energy Reviews. 2011;15:3963-79.
[27] Ogriseck S. Integration of Kalina cycle in a combined heat and power plant, a case study. Applied Thermal Engineering. 2009;29:2843-8.
[28] Bianchi M, De Pascale A. Bottoming cycles for electric energy generation: Parametric investigation of available and innovative solutions for the exploitation of low and medium temperature heat sources. Applied Energy. 2011;88:1500-9.
[29] Handayani TP, Harvey AP, Reay DA, Law R. Opportunities for Organic Rankine cycles in the Process Industries. Proceedings of SusTEM2011, Newcastle, UK. 2011.
[30] Tata Steel. Tata Steel invests in energy-efficient cooling at Port Talbot steelworks [online]. 2011. Available from: http://www.tatasteeleurope.com/en/news/news/2011_pt_energy_efficient_cooling [Accessed 4th January 2012].
[31] Rossetti N. Turboden heat recovery. [Email] (Personal communication, 17th May 2011).
[32] Cengel YA, Boles MA. Thermodynamics. An Engineering Approach. London: McGraw-Hill; 2002.
[33] Thornley P, Walsh C. Addressing the barriers to utilisation of low grade heat from the thermal process industries. (R108105/2010/r02rev03), 2010.
[34] Gerson T. GE Power and Water. [Email] (Personal communication, 19th April 2011).
[35] Simcock M. Freepower. [Email] (Personal communication, 28th April 2011).

[36] Ammar Y, Chen Y, Joyce S, Wang YD, Roskilly AP, Swailes D. Absorption Process: an Efficient Way to Economically Transfer Low Grade Heat from Industrial Sources to Domestic Sinks. Proceedings of SusTEM 2011, Newcastle, UK. 2011.
[37] Ma Q, Luo L, Wang RZ, Sauce G. A review on transportation of heat energy over long distance: Exploratory development. Renewable & Sustainable Energy Reviews. 2009;13:1532-40.
[38] Mazet N, Neveu P, Stitou D. Comparative assessment of processes for the transportation of thermal energy over long distances. Proceedings of ECOS 2010, Lausanne, Switzerland. 2010.
[39] US DOE Industrial Technologies Program. FINAL Public Report for the Energy Savings Assessment for ESA-025. Washington, DC.: US DOE, 2006.
[40] Palmer J, Cooper I. Great Britain's housing energy fact file. London: Department of Energy and Climate Change, 2011.
[41] AEA. 2011 Guidelines to Defra / DECC's GHG Conversion Factors for Company Reporting. London: Department of Energy and Climate Change; 2011.
[42] Carbon Trust. Industrial Energy Efficiency Accelerator - Guide to the maltings sector (CTG053). London: Carbon Trust, 2011.
[43] BERR. ECUK Table 4.7: Industrial energy consumption by end use (different processes), 2005. London: Department for Business, Enterprise and Regulatory Reform; 2008.
[44] McKenna RC. Industrial Energy Efficiency: Interdisciplinary Studies of the Thermodynamic, Technical and Economic Potential [Thesis]: University of Bath; 2009.
[45] IEA. Energy Technology Transitions for Industry. Paris: International Energy Agency; 2009.
[46] AEA. Analysing the Opportunities for Abatement in Major Emitting Industrial Sectors. Report for The Committee on Climate Change. Didcot: AEA, (AEAT/ENV/R/Industrial Energy Efficiency), 2010.
[47] Werner S. District Heating and Cooling. In: Cleveland CJ, editor. Encyclopedia of Energy, Volumes 1 - 6: Elsevier; 2004.
[48] Speirs J, Gross R, Deshmukh S, Heptonstall P, Munuera L, Leach M, et al. Building a roadmap for heat: 2050 scenarios and heat delivery in the UK. London: The Combined Heat and Power Association, 2010.
[49] This is South Wales. Power from Corus steelworks could generate heating for Port Talbot homes [online]. 2010. Available from: http://www.thisissouthwales.co.uk/Power-steelworks-generate-heating-houses/story-12435607-detail/story.html [Accessed 15th November 2011].
[50] Future Energy Solutions. Assessment of Emerging Innovative Energy Efficient Technologies as part of the Energy Efficiency Innovation Review. London: DEFRA, (AEAT/ENV/R/2001), 2005.
[51] Rohdin P, Thollander P. Barriers to and driving forces for energy efficiency in the non-energy intensive manufacturing industry in Sweden. Energy. 2006;31:1836-44.
[52] DeCanio SJ. Barriers within firms to energy-efficient investments. Energy Policy. 1993;21:906-14.
[53] Van Soest DP, Bulte EH. Does the energy-efficiency paradox exist? Technological progress and uncertainty. Environmental and Resource Economics. 2001;18:101-12.
[54] Ammar Y, Joyce S, Norman R, Wang Y, Roskilly AP. Low grade thermal energy sources and uses from the process industry in the UK. Applied Energy. 2012;89:3-20.